Higgs measurement with the CEPC Ref-TDR

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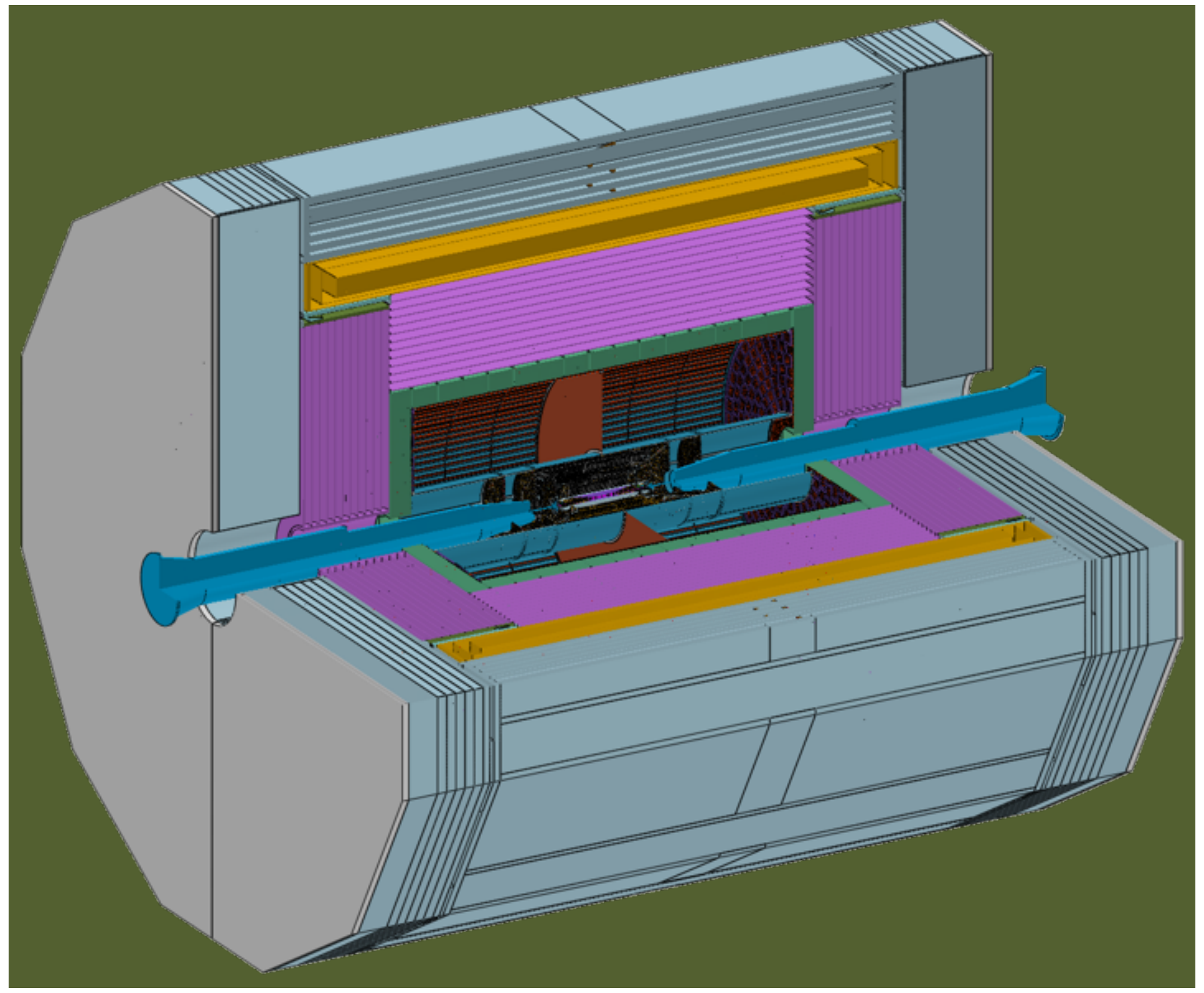
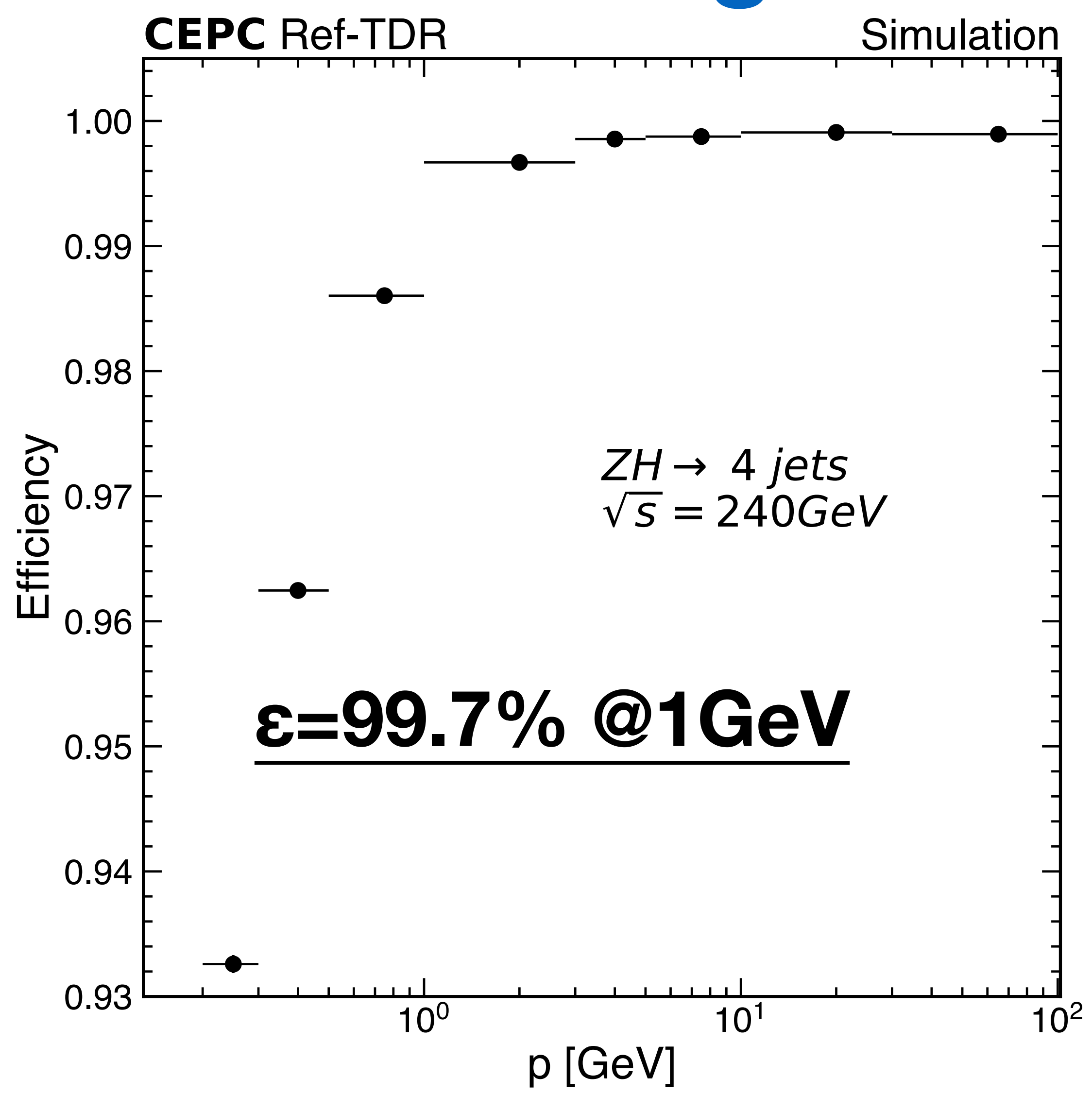
Introduction

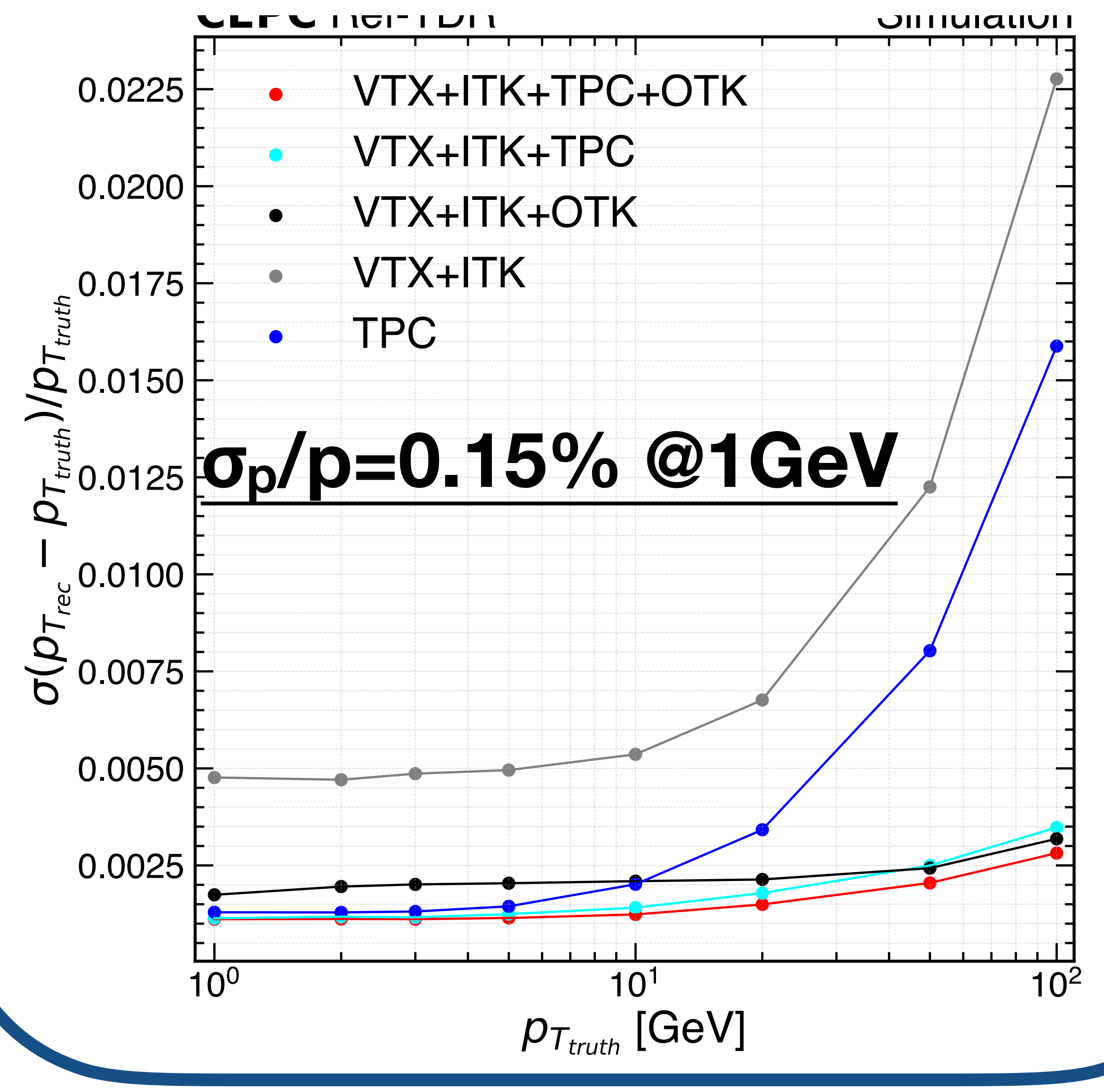


- ◈ Design the sub-detectors with a detail engineering consideration
  - ✦ Mechanical support structures, electronics, cabling etc
- ◈ Full simulation as realistic as possible
- ◈ All events are reconstructed using a sophisticated reconstruction chain
  - ✦ Kalman-filter based track reconstruction and CyberPFA

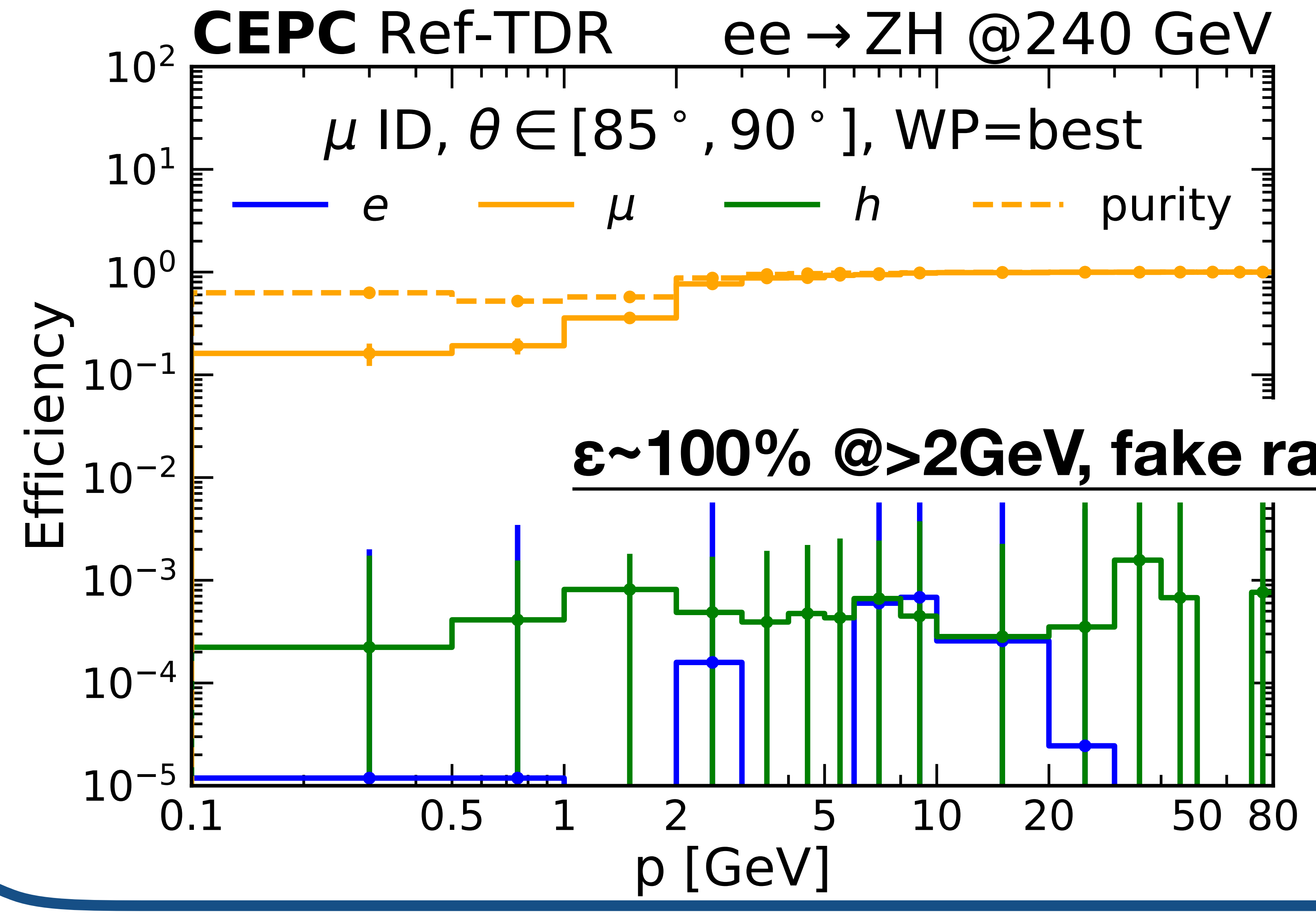
Performance

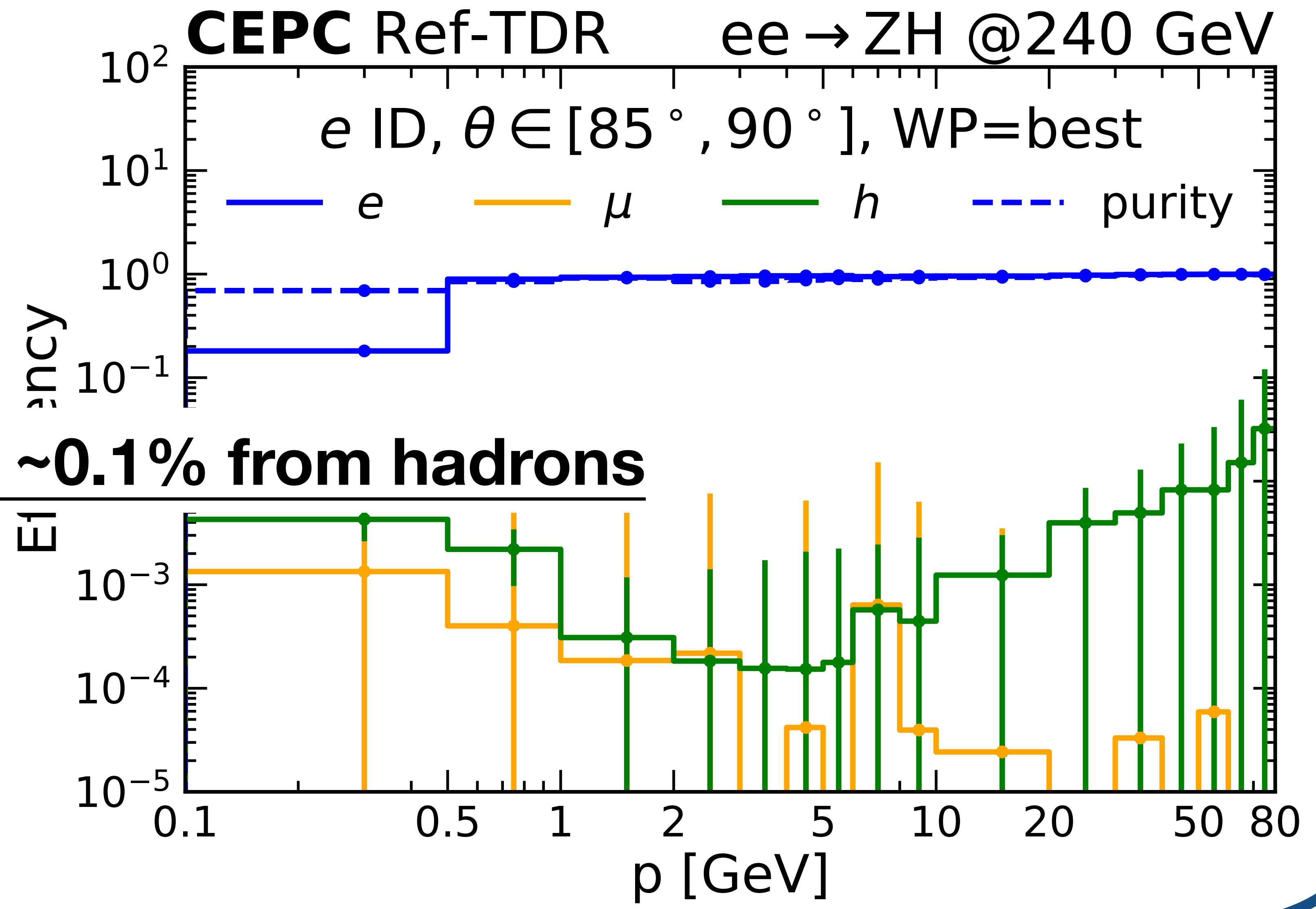
Tracking





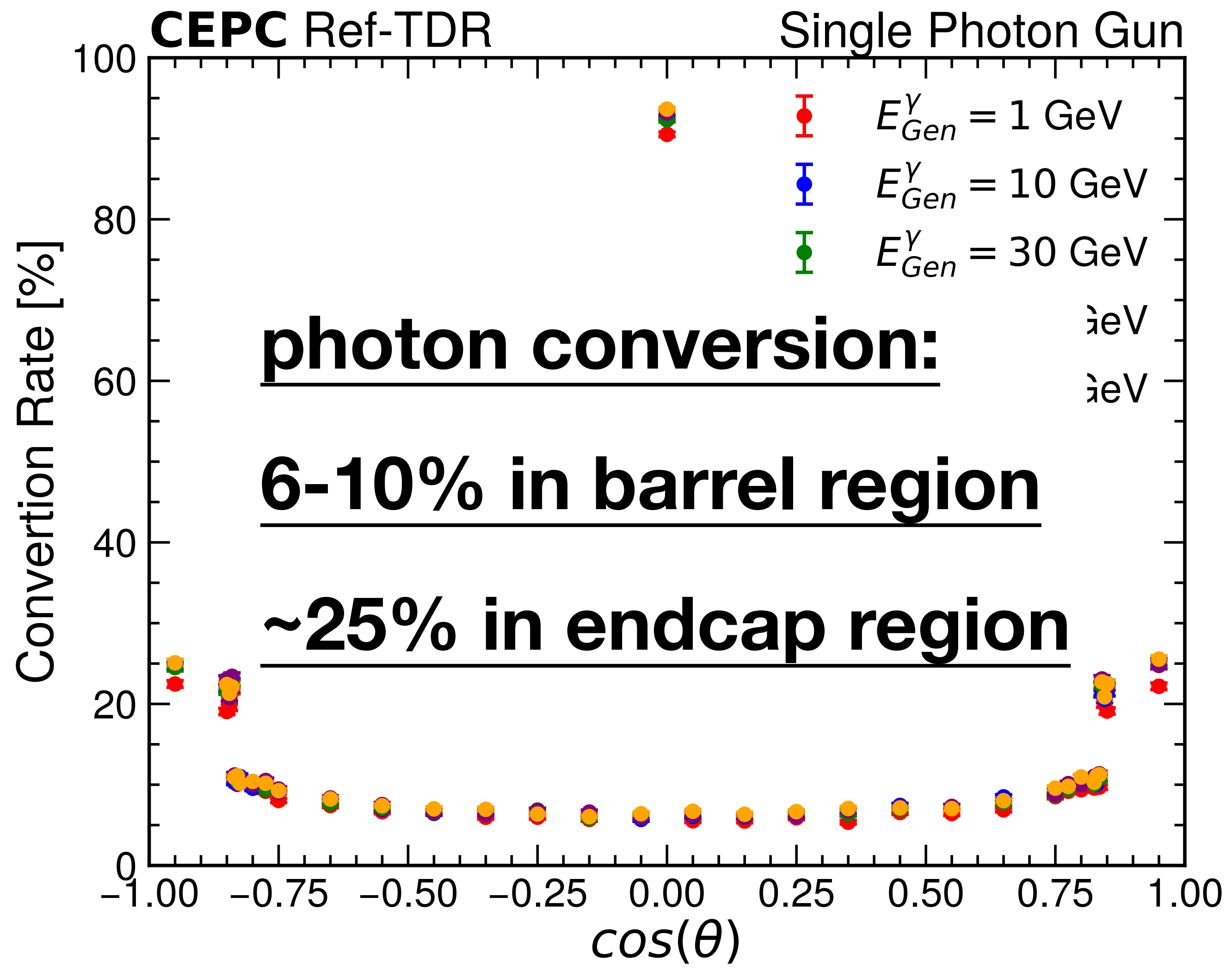
Lepton

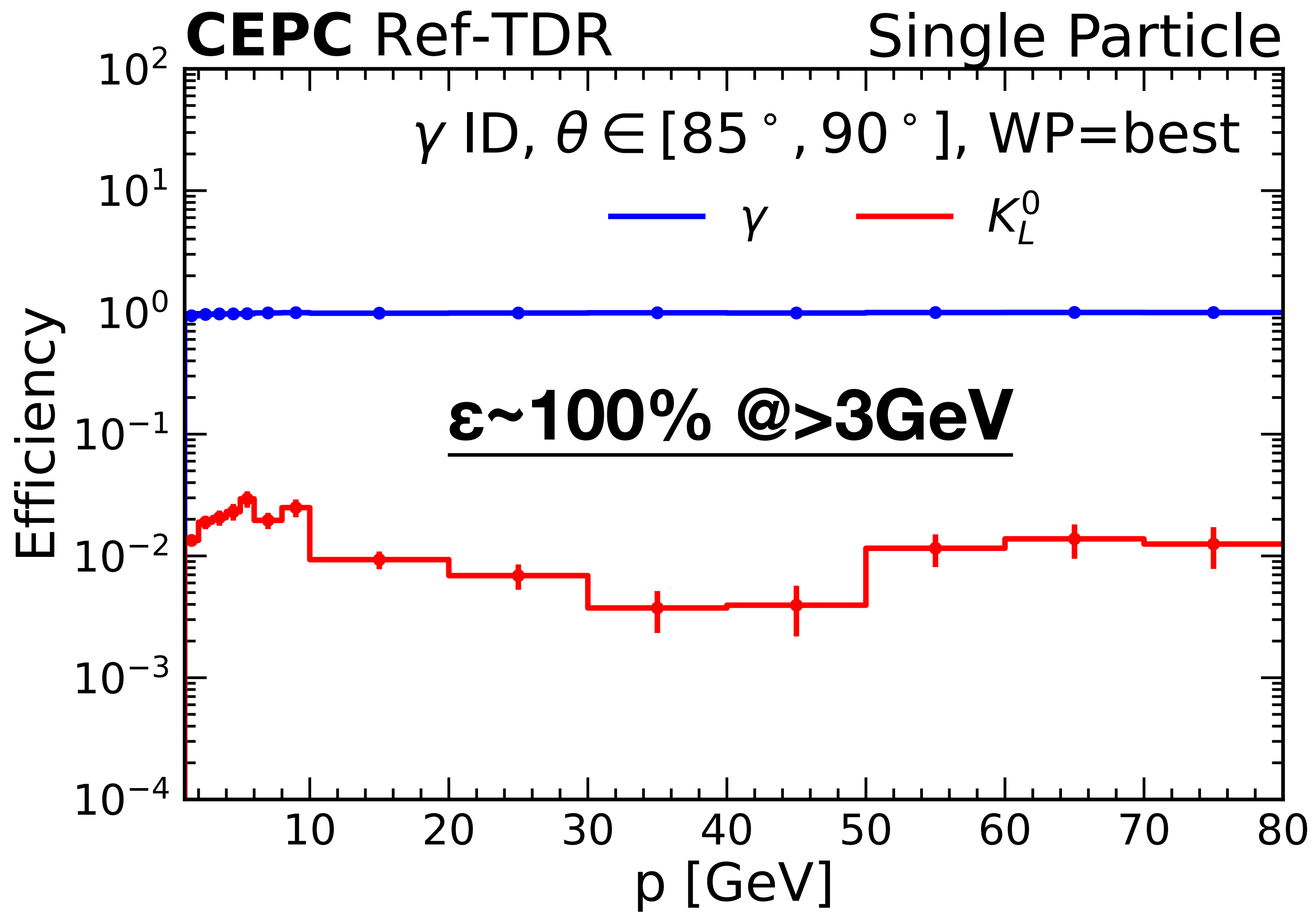




ε~100% @>2GeV, fake rate ~0.1% from hadrons

Photon

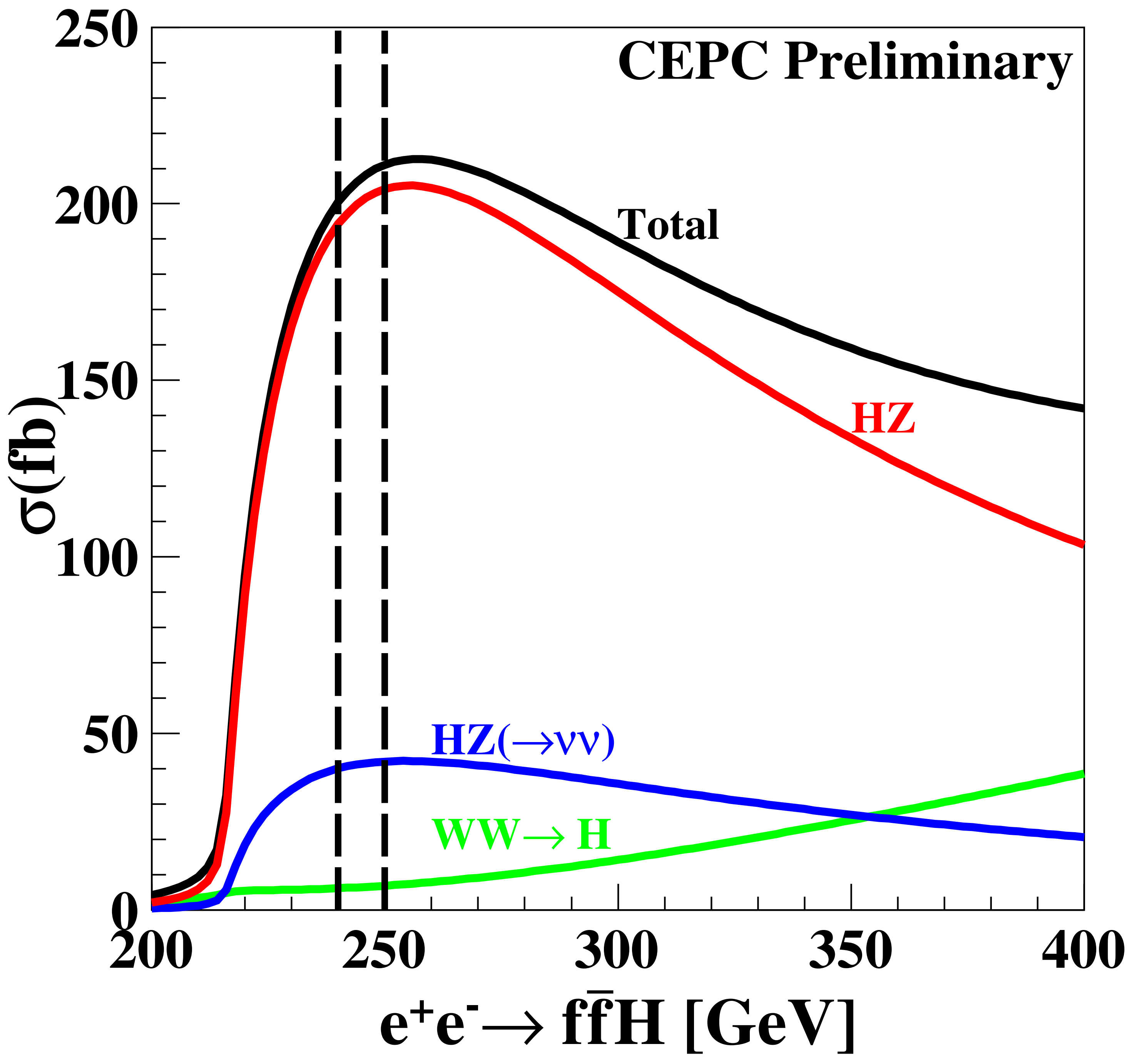


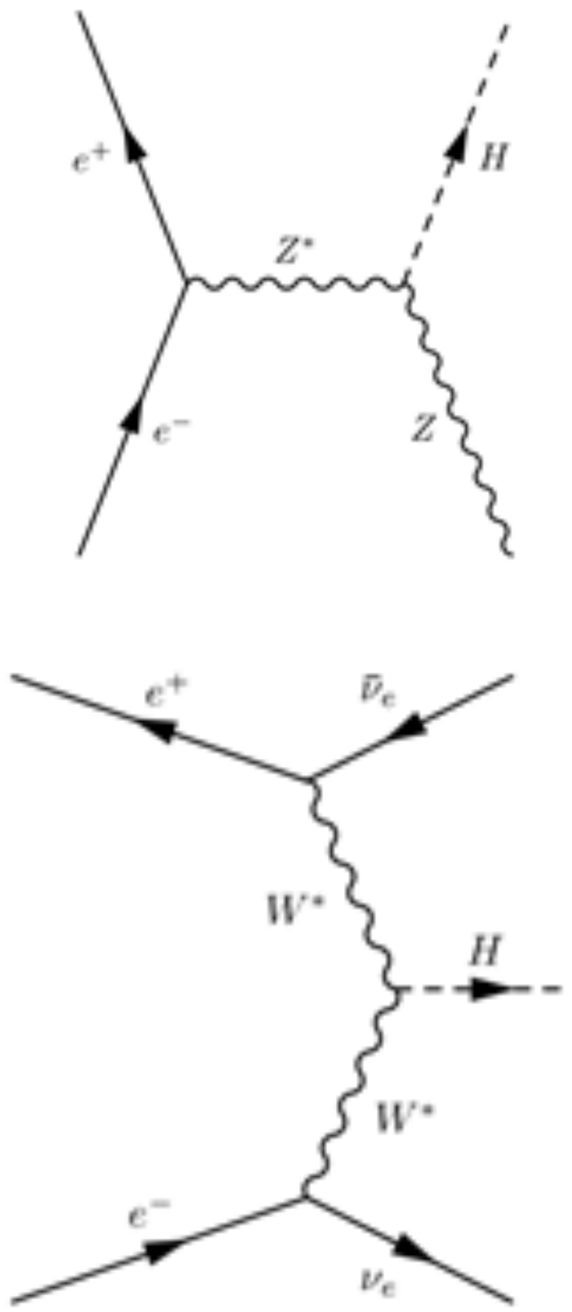


Outline

- Higgs mass measurement via recoil mass
- Branching ratio measurement in hadronic final states
- $H \rightarrow \gamma\gamma$ measurement
- $H \rightarrow$ invisible measurement

Physics Processes





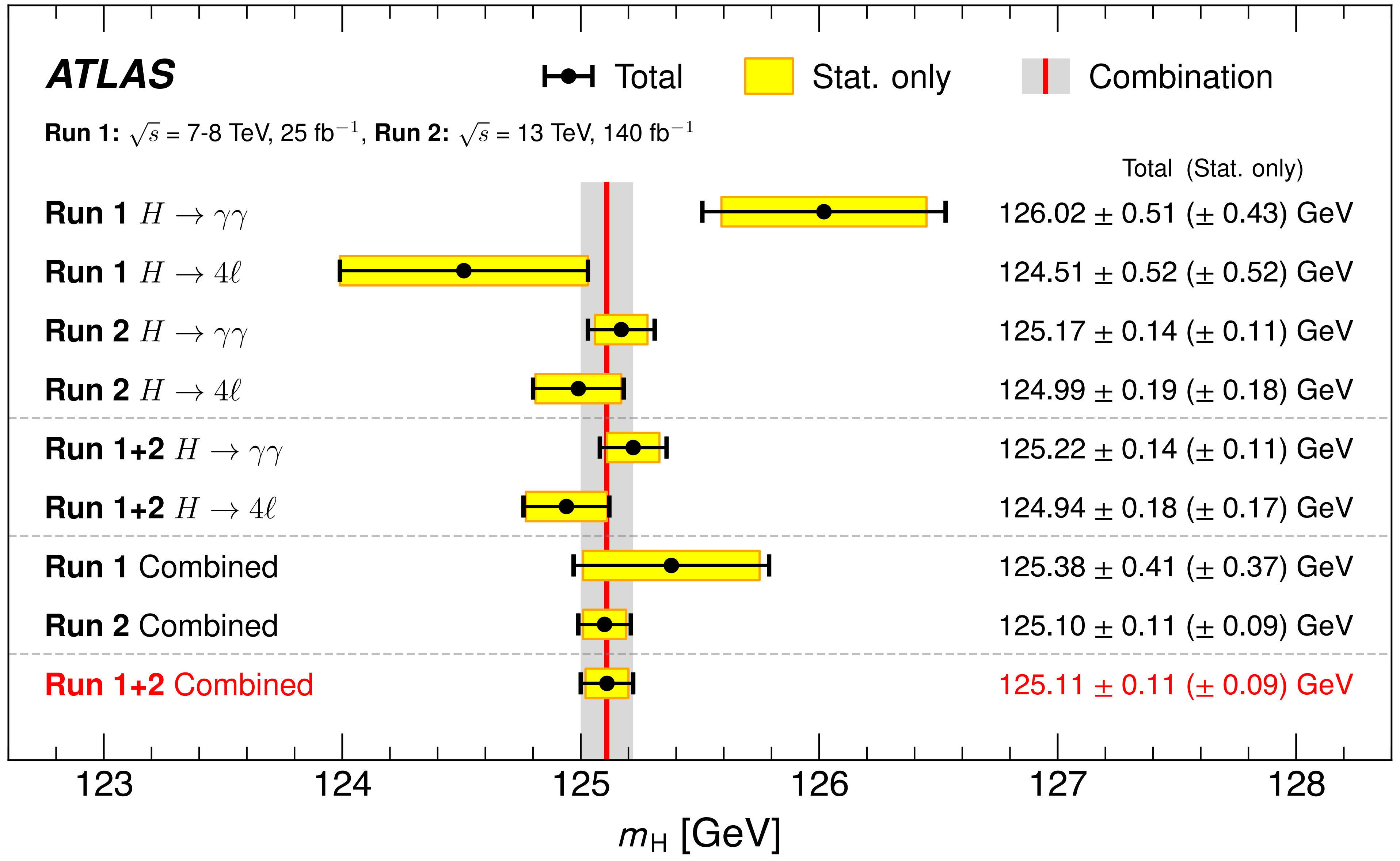
Process	Cross section @ 240 GeV	Cross section @ 360 GeV
Higgs boson production, cross section in fb		
$e^+e^- \to ZH$	196.9	126.6
$e^+e^- \to \nu_e\bar{\nu}_e H$	6.2	29.6
$e^+e^- \to e^+e^- H$	0.5	2.8
Total Higgs	**203.6**	**159.0**
background processes, cross section in pb		
$e^+e^- \to e^+e^-(\gamma)$ (Bhabha)	930	325
$e^+e^- \to q\bar{q}(\gamma)$	54.1	23.0
$e^+e^- \to \mu^+\mu^-(\gamma)$	5.30	2.4
$e^+e^- \to \tau^+\tau^-(\gamma)$	4.75	2.1
$e^+e^- \to t\bar{t}$	–	0.566
$e^+e^- \to WW$	16.7	11.3
$e^+e^- \to ZZ$	1.1	0.68
$e^+e^- \to e^+e^- Z$	4.54	5.83
$e^+e^- \to e^+\nu W^- +$ c.c.	5.09	6.04

WHIZARA1.9.5 event generator for cross section calculation and MC sample generation

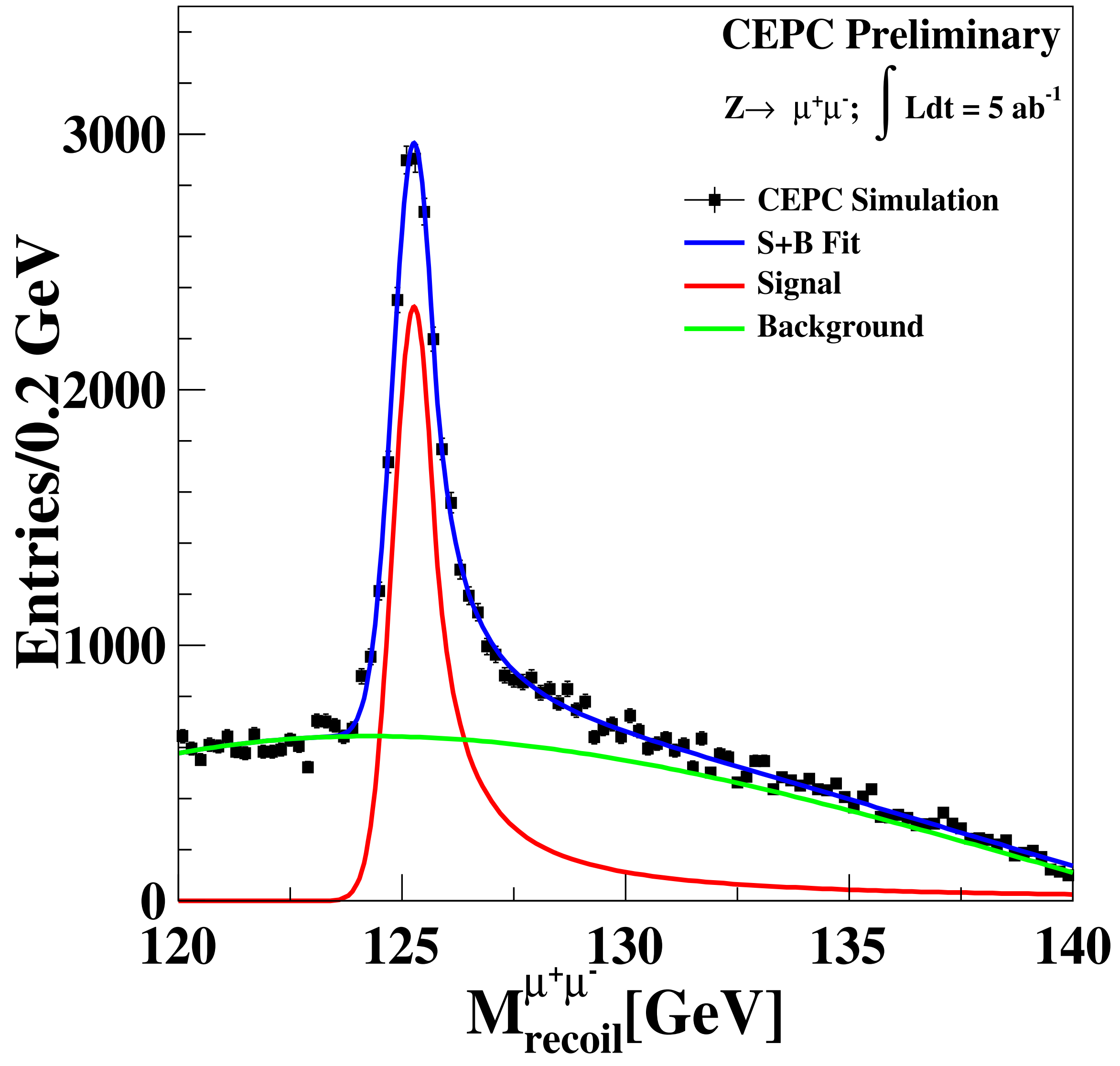
- Higgs signal production: Higgsstrahlung ($e^+e^- \to ZH$), W-boson fusion ($e^+e^- \to \nu\nu H$), and Z-boson fusion ($e^+e^- \to e^+e^- H$)
- Background process:
  - $e^+e^- \to$ 2-fermion: e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$ and $q\bar{q}$
  - $e^+e^- \to$ 4-fermion: WW production ($e^+e^- \to W^+W^- \to 4f$),ZZ production ($e^+e^- \to ZZ \to 4f$), Single W production ($e^+e^- \to We\nu$), Single Z production ($e^+e^- \to Zee$)

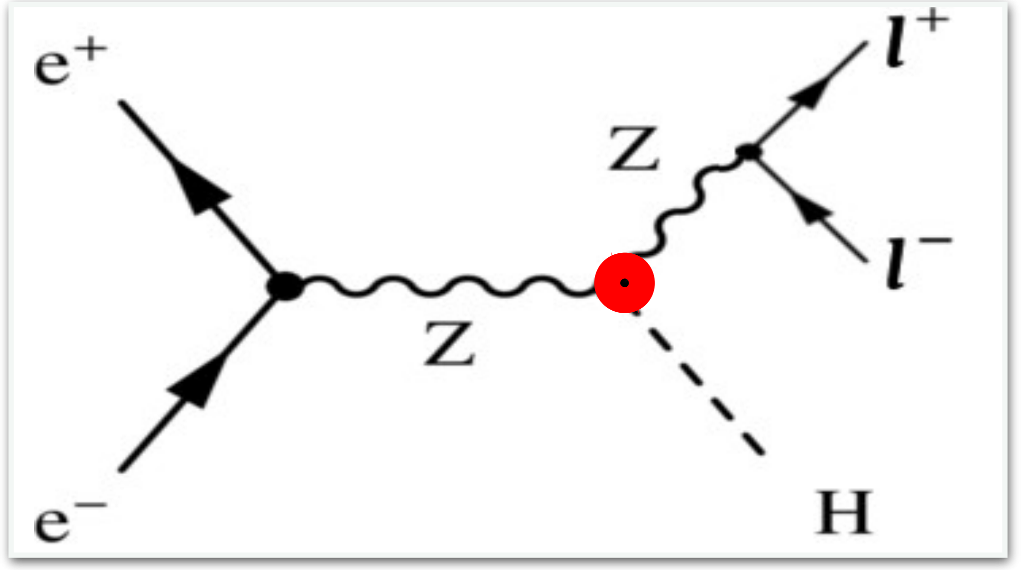
Higgs mass

The free parameter of SM Higgs sector, related to fundamental property of elementary particles



PRL131(2023)251802





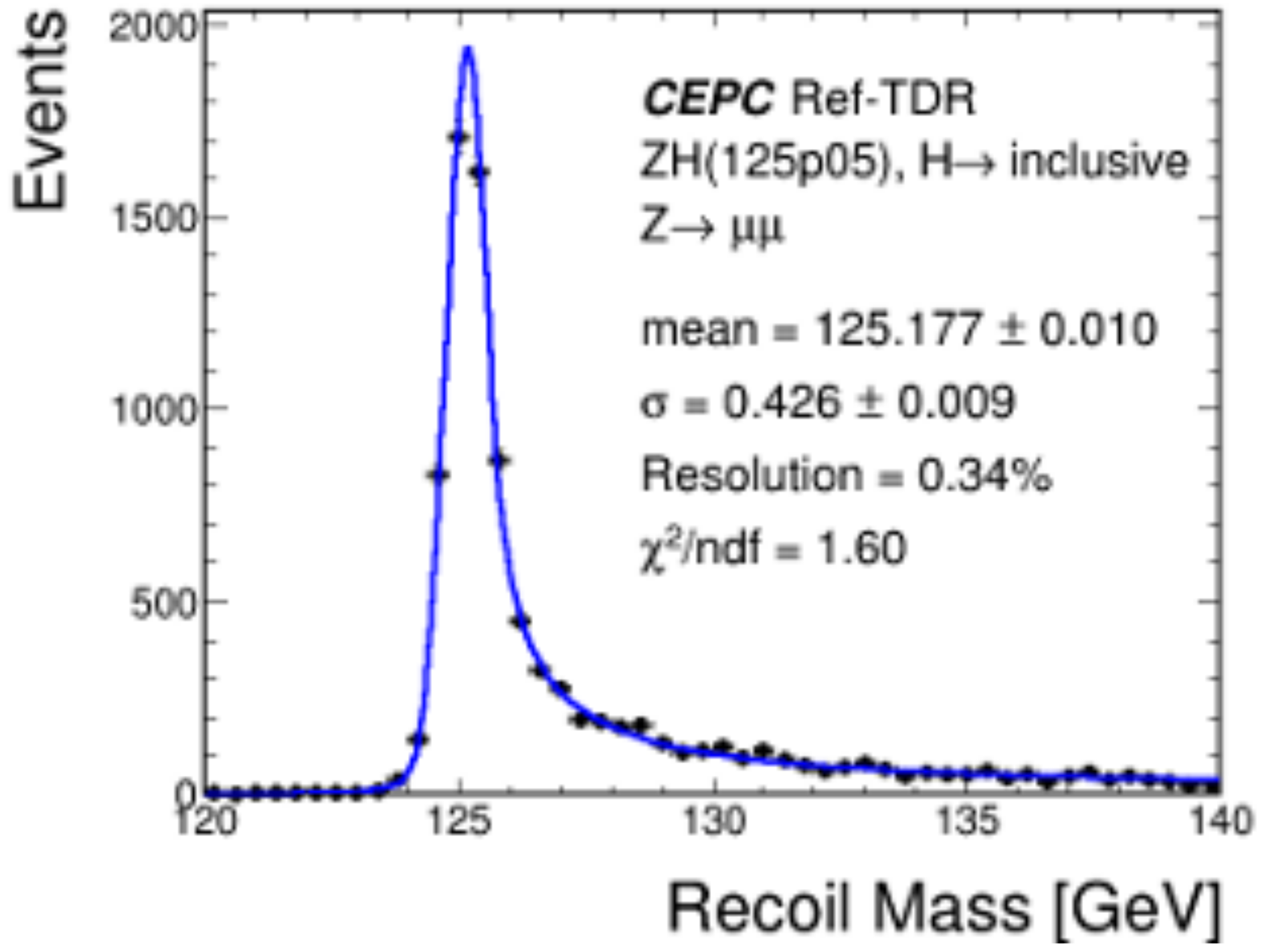
- Even neglecting the statistical uncertainty, Δm_H @ LHC can only reach ~50 - 80 MeV
- In the lepton collider, m_H can be reconstructed with the recoil mass method

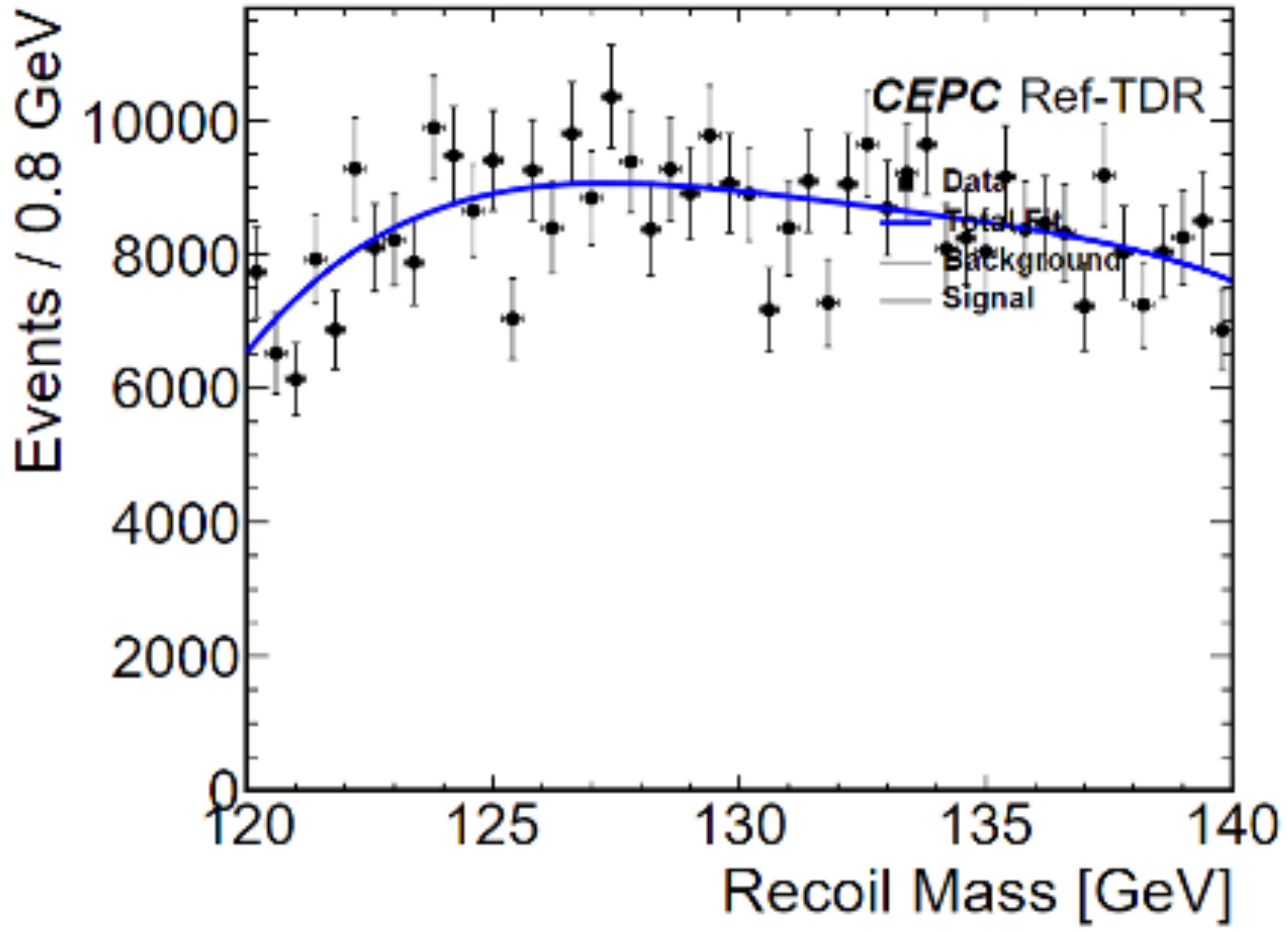
mass precision (Δm_H)

HL-LHC* 14 TeV (3 ab^{-1})	FCC-ee Baseline (10 yrs)	ILC Lumi upgrade (20 yrs)	CEPC Baseline (10 yrs)	CLIC Baseline (15 yrs)
50 MeV	4 MeV	15 MeV	5.9 MeV	32 MeV

Mass measurement from CEPC Ref-TDR

Based on Higgs-strahlung process $e^+e^- \to ZH$ with $\sqrt{s}$ =240GeV and $Z \to \mu^+\mu^-$



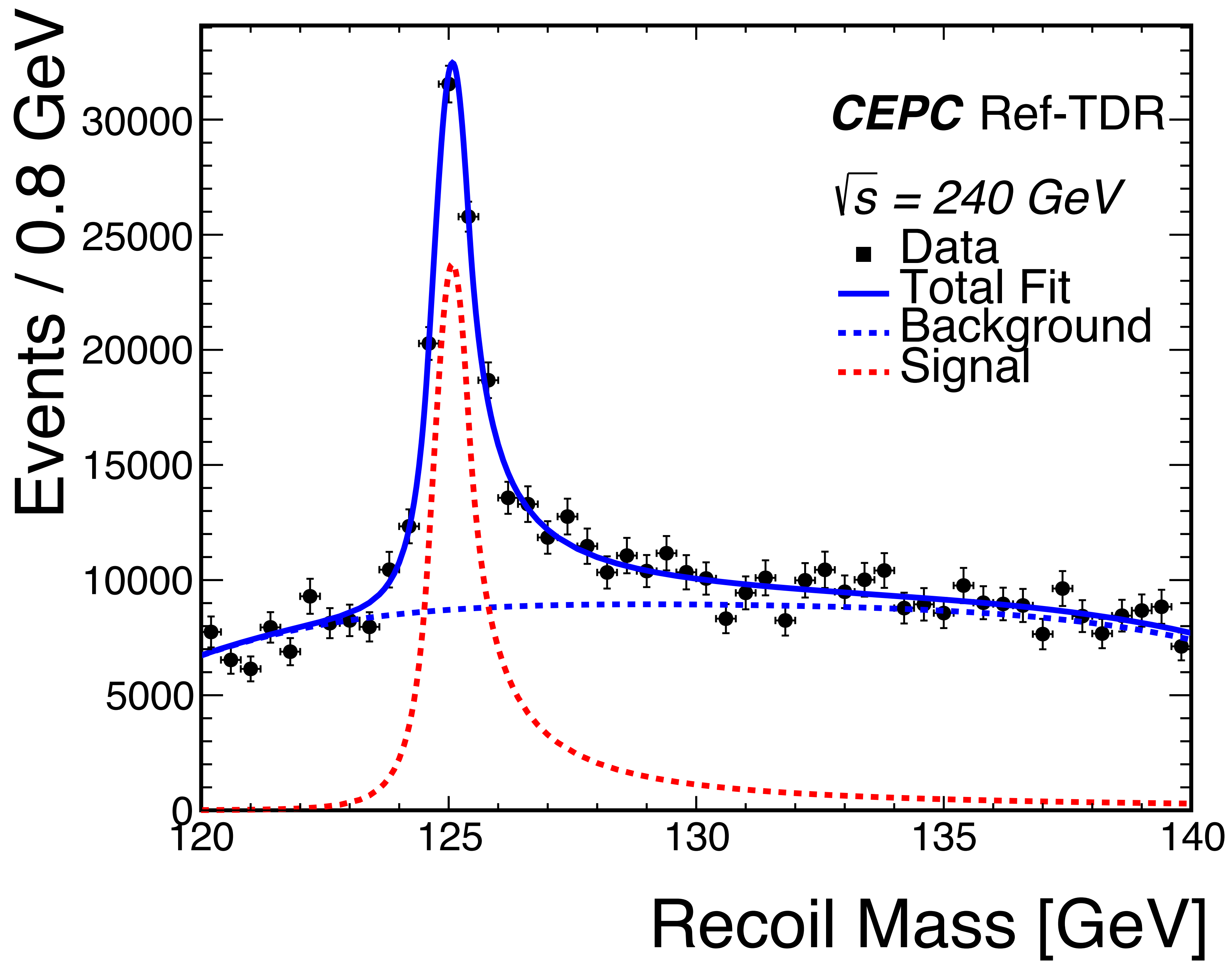


Final States	$2\nu2\mu$	4μ	$2\mu2e$	$2\mu2q$	2μ	$\mu\mu H$
Events number	120000	40000	40000	80000	100000	40000
Muon pair	31.4%	41.7%	6.7%	29.5%	88.2%	95.6%
$M_{rec} \in [110, 150]$ GeV	5.8%	8.5%	1.1%	3.4%	42.0%	88.2%
MEZ $\in [0, 50]$ GeV	4.7%	5.9%	0.7%	3.0%	25.8%	87.1%
$E_{\mu\mu} \in [0, 110]$ GeV	4.1%	5.1%	0.7%	3.0%	25.3%	86.6%
$p_{\mu\mu} \in [20, 60]$ GeV	2.7%	3.4%	0.4%	2.2%	6.5%	78.7%
$m_{\mu\mu} \in [50, 120]$ GeV	2.6%	3.2%	0.1%	1.7%	6.5%	78.7%

$$M^2_{\text{rec}} = (\sqrt{s} - E_{\mu^-} - E_{\mu^+})^2 - |\vec{p}_{\mu^-} + \vec{p}_{\mu^+}|^2$$

- ◈ Mass measurement via the recoiling mass of $Z \to \mu\mu$ based on 20ab^{-1}:
  - ✦ Simple cut-base selections with the momentum of di-muon system
  - ✦ A high signal efficiency of ~80% with a clear Higgs signal on top of continuous background

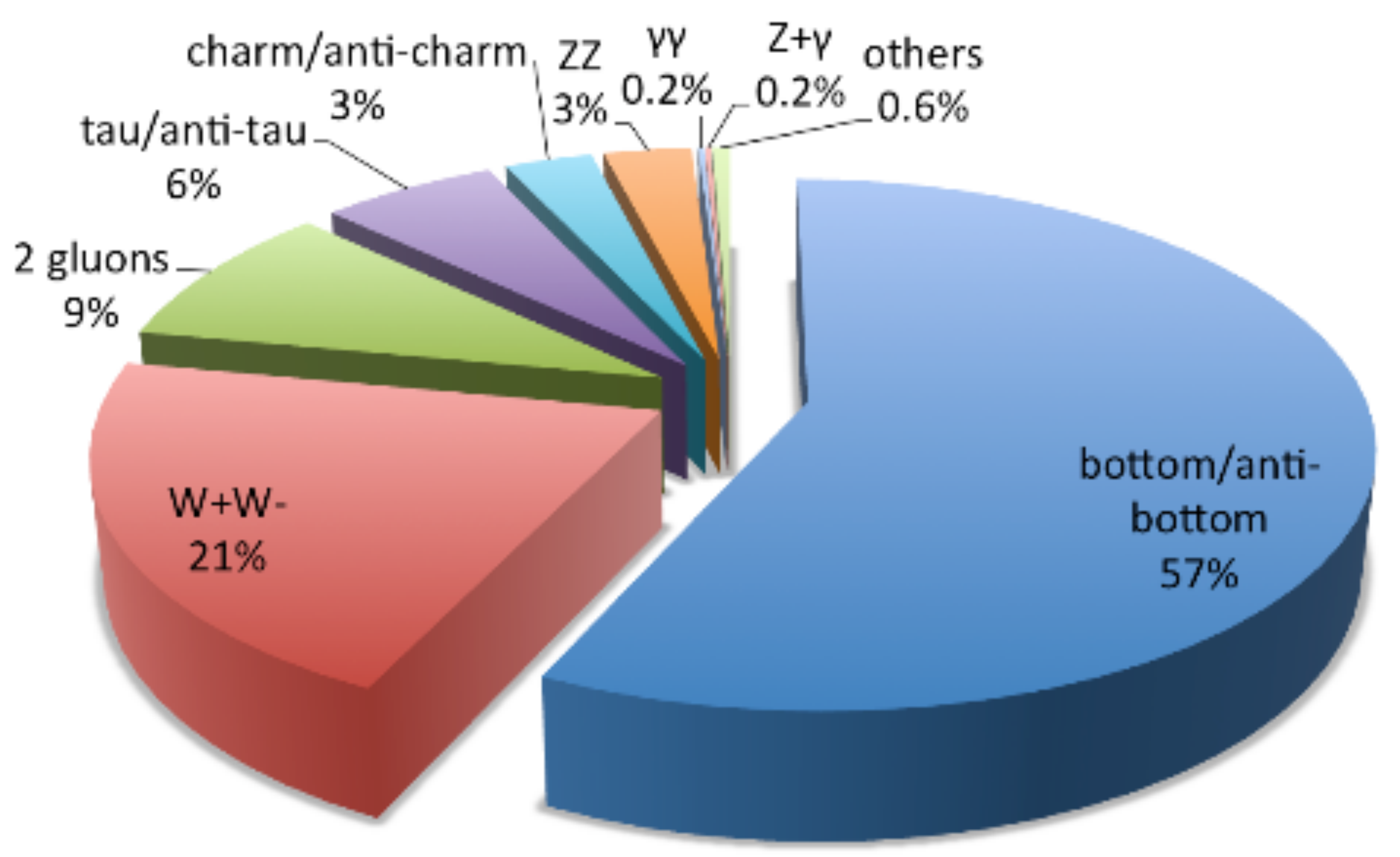
Systematics estimation for Higgs mass measurement

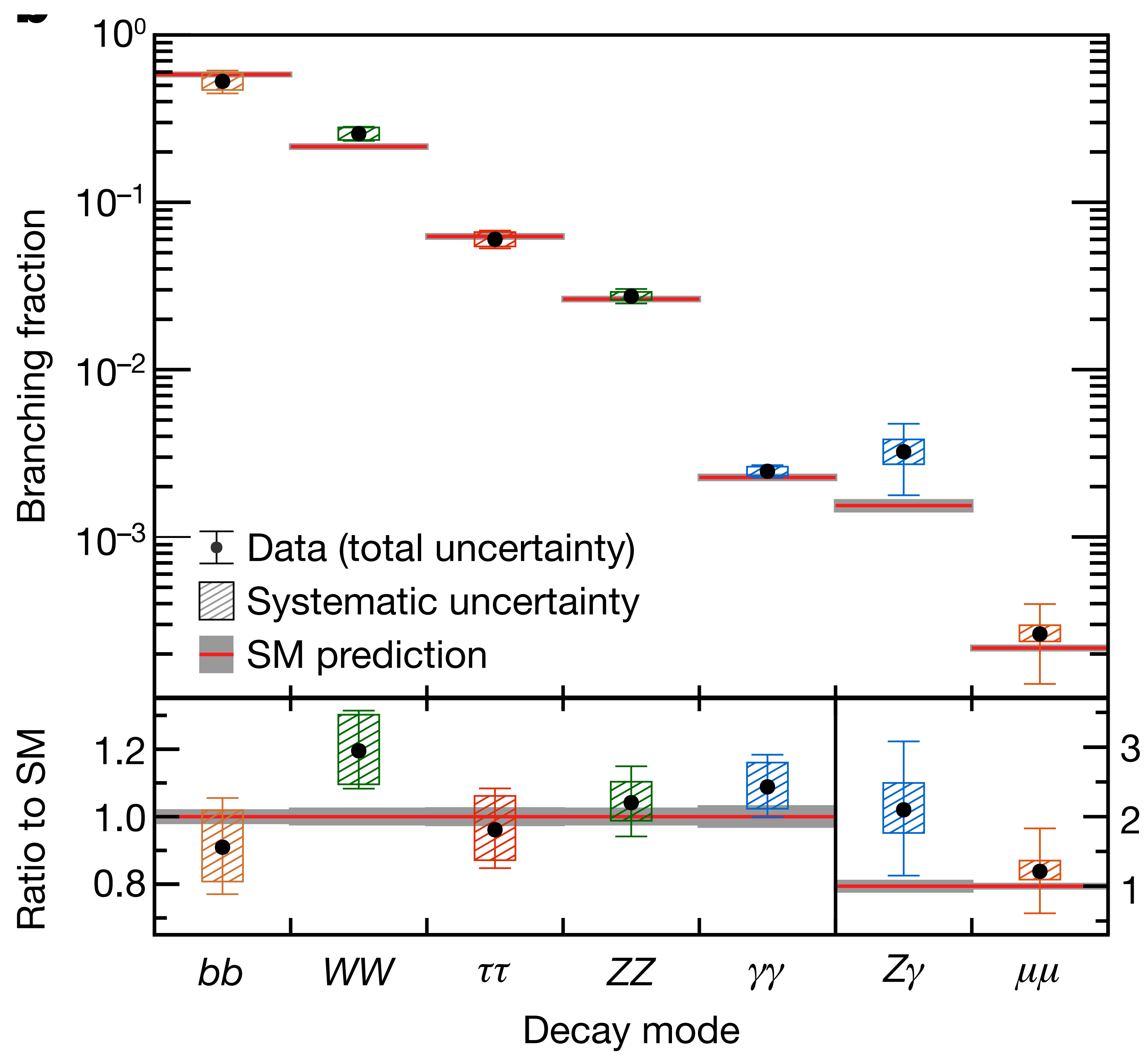


- Momentum scale uncertainty: 2MeV
  - $\delta_{Z_{peak}} = \frac{\sigma_{p_T}}{\sqrt{N}}$, $\sigma_{p_T} = 2 \times 10^{-3}$ with ~3×10^7 radiative return events @ 240GeV
  - Together with low-Lumi Z events, δ_{p_T} ~ 10^{-6} is easily visible from Z boson
- Central-of-mass energy uncertainty: 2MeV
  - $\delta\sqrt{s} : \delta mH \sim 1 : 1$
- Beam Energy Spread uncertainty:
  - Beam energy spread is ~0.17% @240GeV,
- Initial state radiation: 1MeV

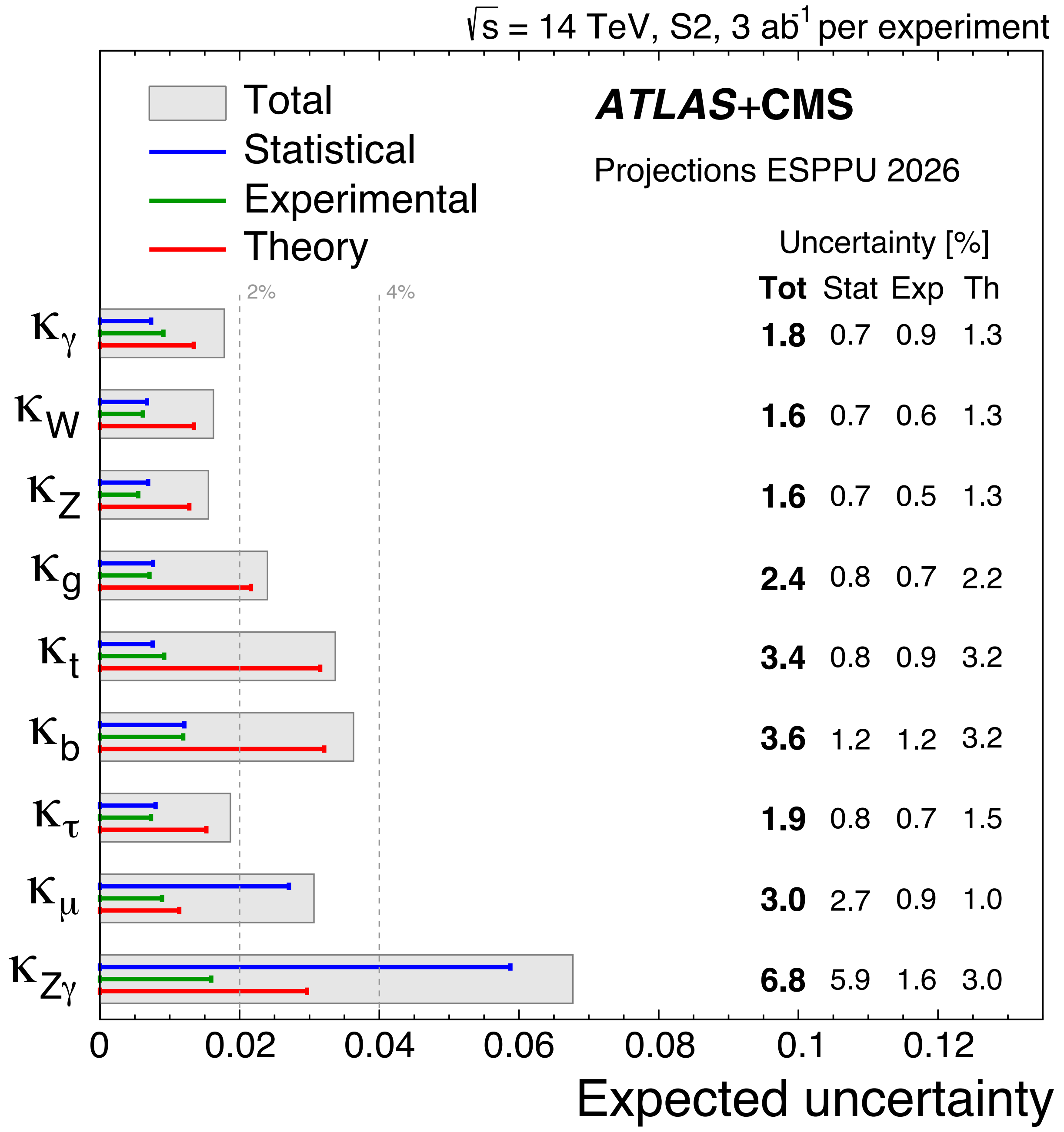
$M_H = 125 GeV \pm 3.1 MeV(stat.) \pm 3.7 MeV(sys.)$ **with the final precision of 4.8MeV**

Branching ratio measurement in hadronic final states





Nature 607(2022)52



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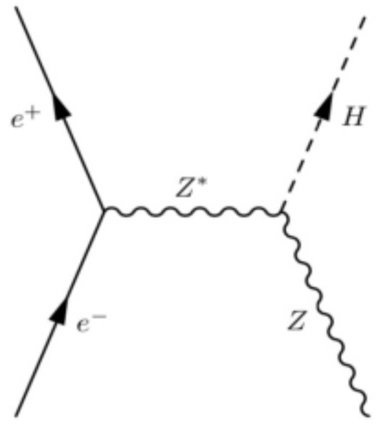
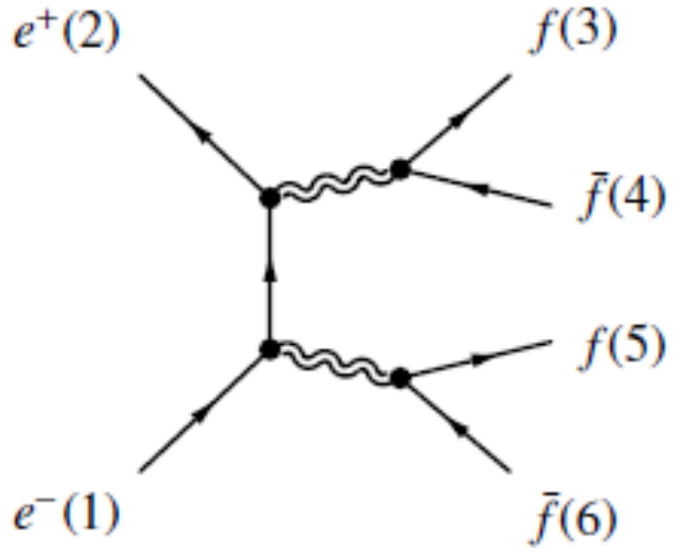
Sig	$H\to b\bar{b}$	$H\to c\bar{c}$	$H\to gg$	$H\to ZZ^*$	$H\to WW^*$	$H\to s\bar{s}$
predictions	57.7%	2.91%	8.57%	2.64%	21.5%	4.4×10^{-4}

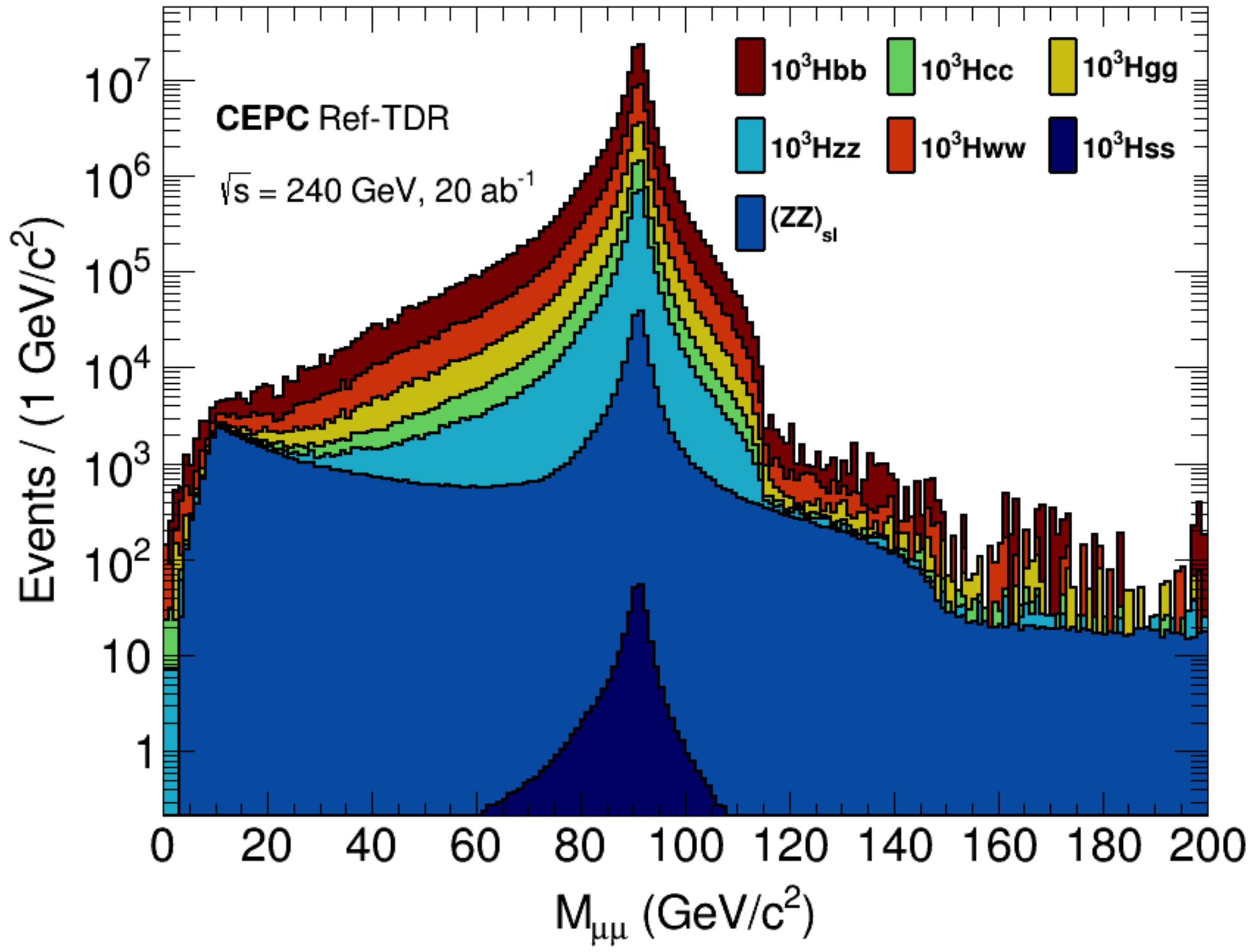
- Higgs decays dominated with the hadronic final states: $H\to b\bar{b}$, $H\to gg$, $H\to c\bar{c}$, $H\to s\bar{s}$ and $H\to WW^*/ZZ^*$ with W/Z hadronic decays
- Difficulty: distinguish with different Jet flavor and contamination among them

Selection for hadronic final states

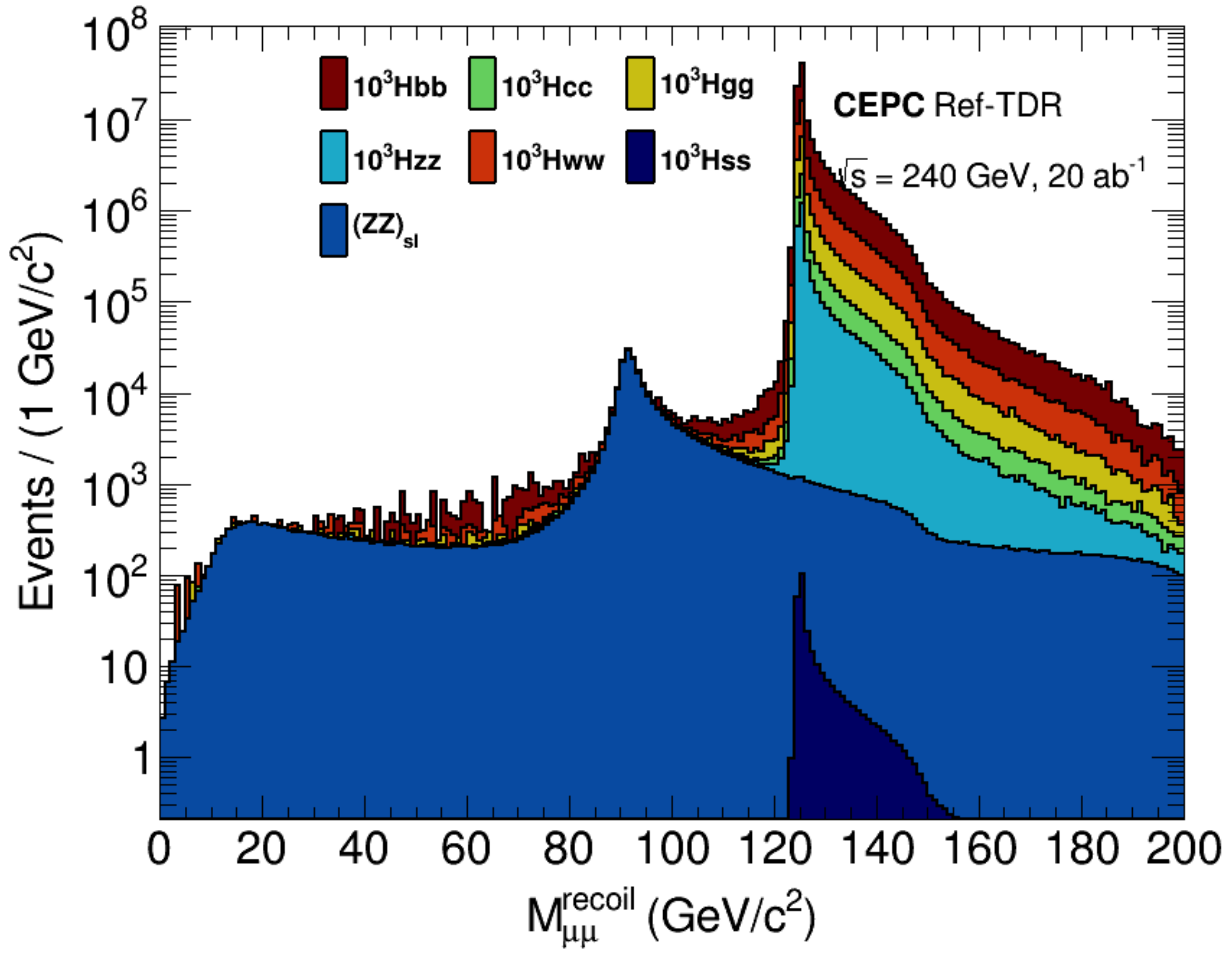




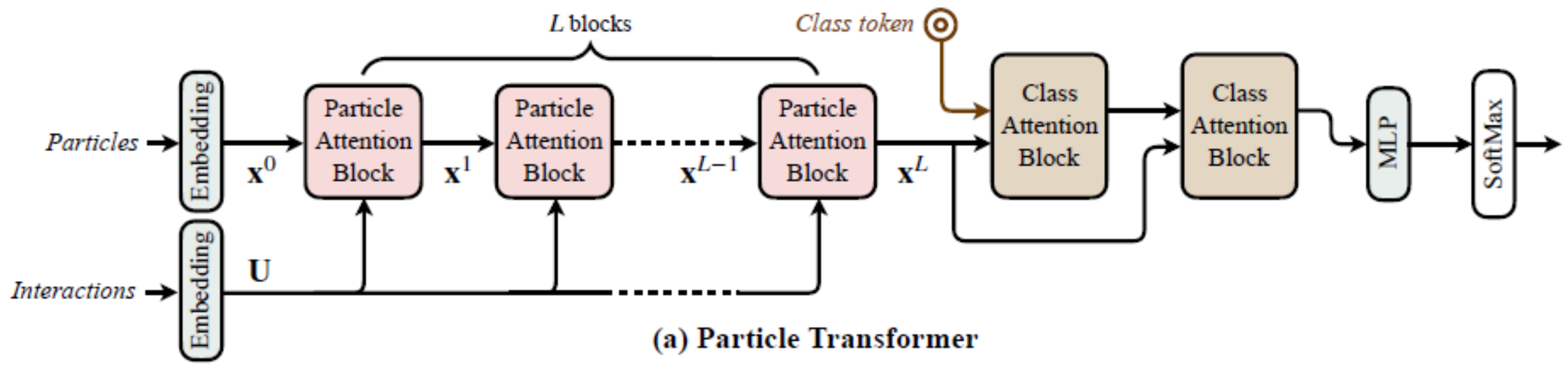
Process	$H\to b\bar{b}$	$H\to c\bar{c}$	$H\to gg$	$H\to ZZ^*$	$H\to WW^*$	$H\to s\bar{s}$	$(ZZ)_{sl}$
Theo. N	78126	3940	11604	3575	29111	60	11129800
Simu. N	495000	494500	371500	497250	497000	494250	26499801
Muon pair	96.9%	96.7%	96.7%	96.7%	96.7%	96.6%	18.8%
Isolation	90.3%	90.3%	90.5%	90.7%	90.4%	90.5%	12.9%
Z-mass	86.7%	86.7%	86.9%	87.1%	86.8%	86.8%	9.1%
H-mass	86.4%	86.3%	86.5%	86.7%	86.4%	86.5%	1.5%
$\cos\theta$	86.1%	86.0%	86.2%	86.4%	86.1%	86.2%	1.5%
N_{charged}	86.1%	86.0%	86.2%	86.4%	86.1%	86.1%	1.5%



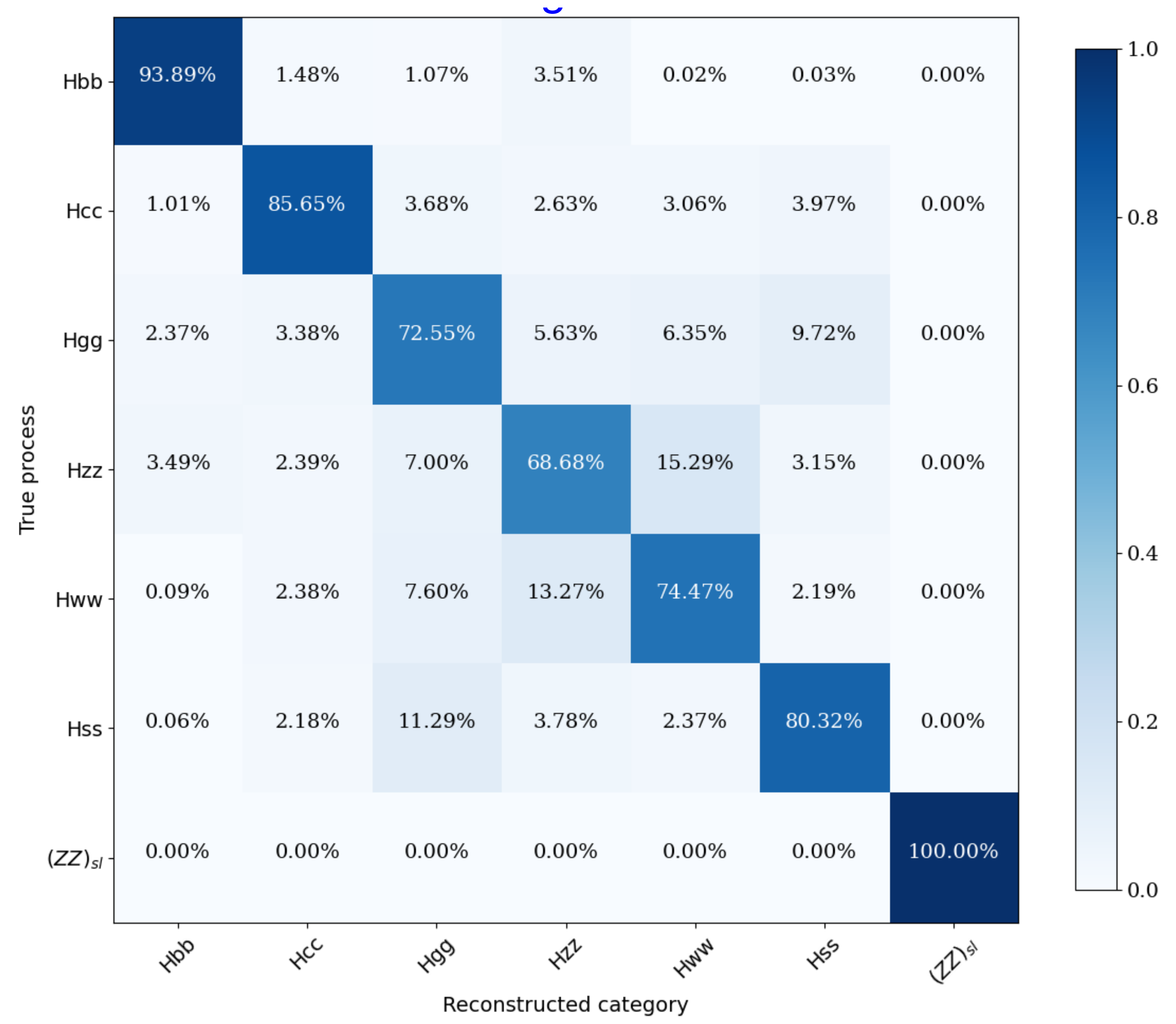
- Focus on the signature of ZH ($Z\to\mu\mu$)
- Selection based on muon reconstruction information:
  - Signal efficiency ~86% for different modes
  - Main background from $(ZZ)_{sl}$



Simultaneous measurement



(a) Particle Transformer

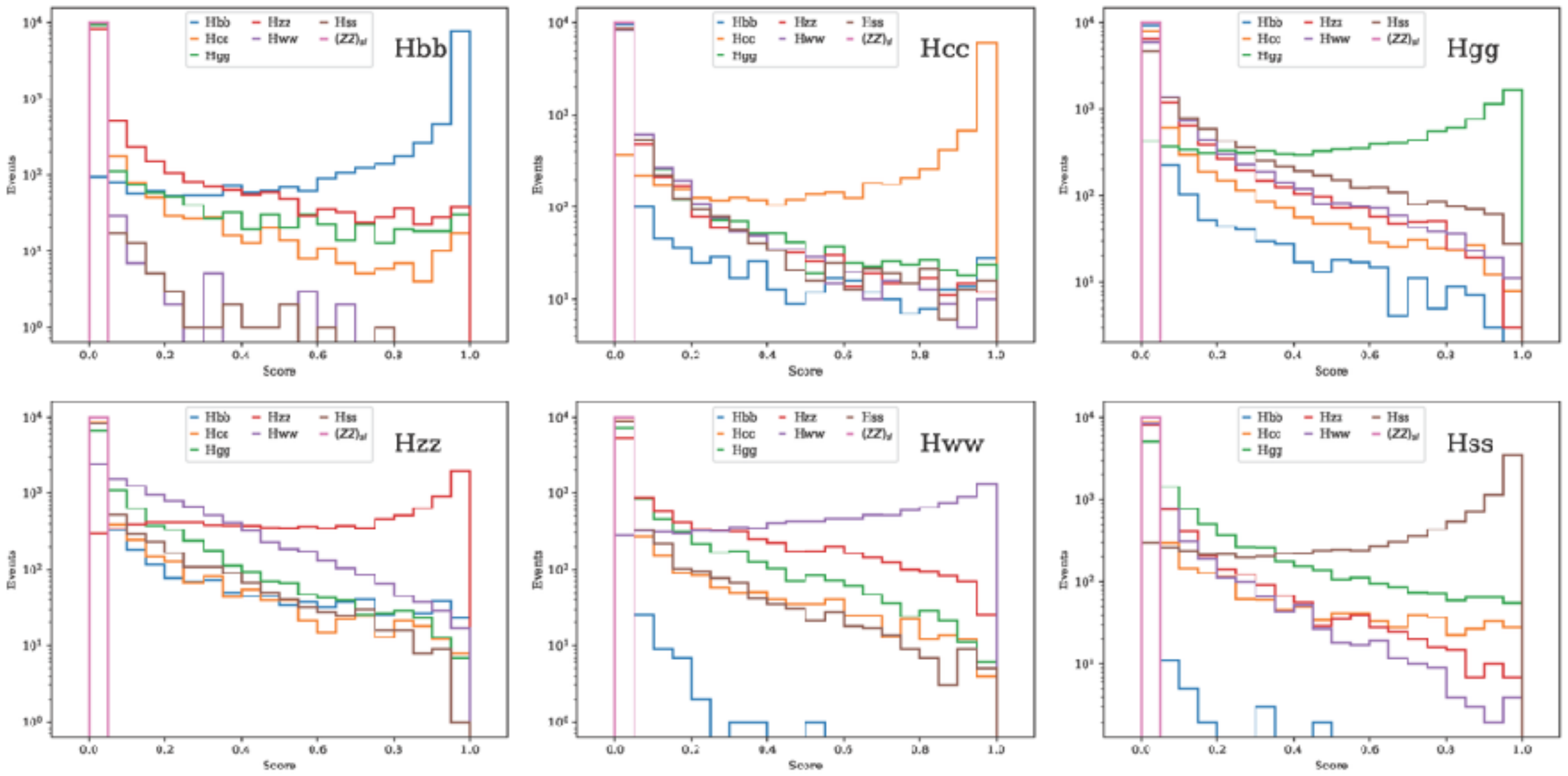


Tracking: E, P, $cos\theta$, ϕ, PID, D_0, Z_0, charge, ZTag

Edge feature: Pt, η, ϕ, E

- ◈ Multi-classification of different modes with Particle Transformer
  - ✦ Simultaneous measurement on signal and background from contamination
- ◈ Training variables based on the basic information of all tracks:
  - ✦ High correction rate for bb (~94%)

Measurement of Higgs decays with hadronic final states



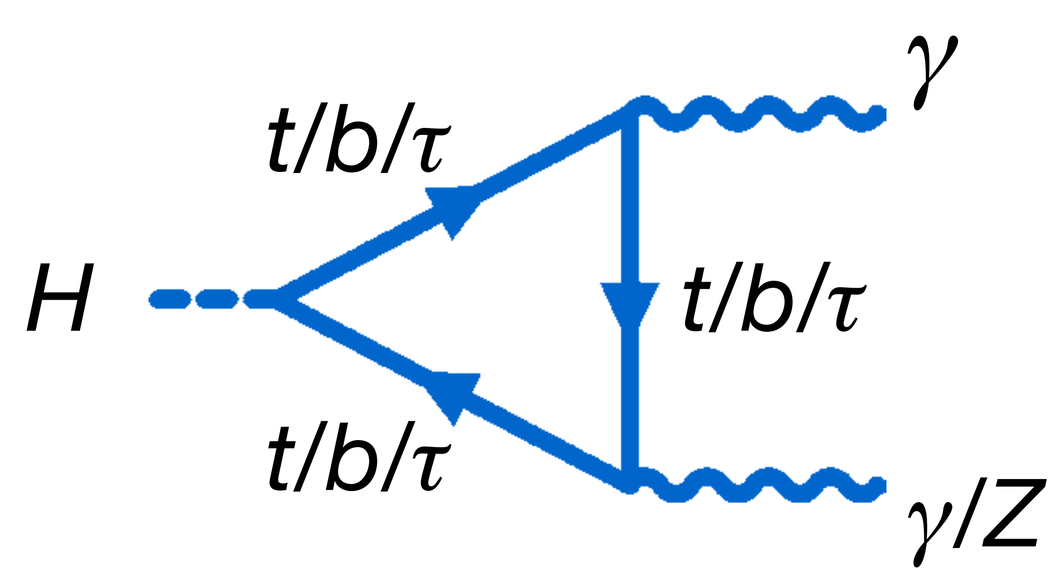
- Good separation among different signal mode and background
- Based on simple counting and unfolding method, achieve ~0.3% precision for $H \to b\bar{b}$
- Taking into account 20% position uncertainty for tracking, ~0.1% systematic uncertainty for $H \to b\bar{b}$
- More promising precision is expected with the MVA score shape information

$$\begin{bmatrix} N_{s1} \\ N_{s2} \\ \cdots \\ N_{b1} \\ N_{b2} \\ \cdots \end{bmatrix} = \left(M_{mig}^{T} M_s\right)^{-1} \times \begin{bmatrix} n_{s1} \\ n_{s2} \\ \cdots \\ n_{b1} \\ n_{b2} \\ \cdots \end{bmatrix}$$

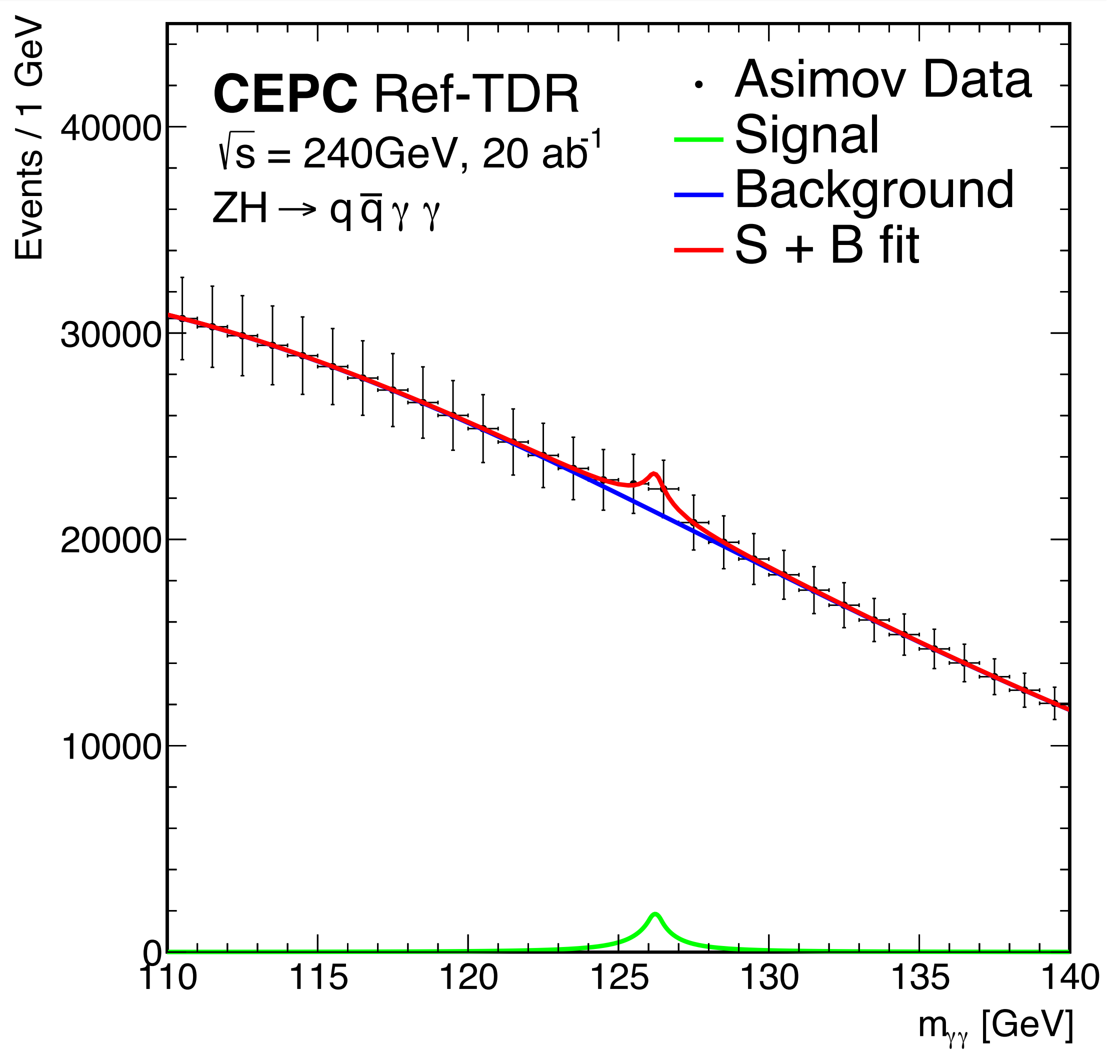
Migration matrix unfolding

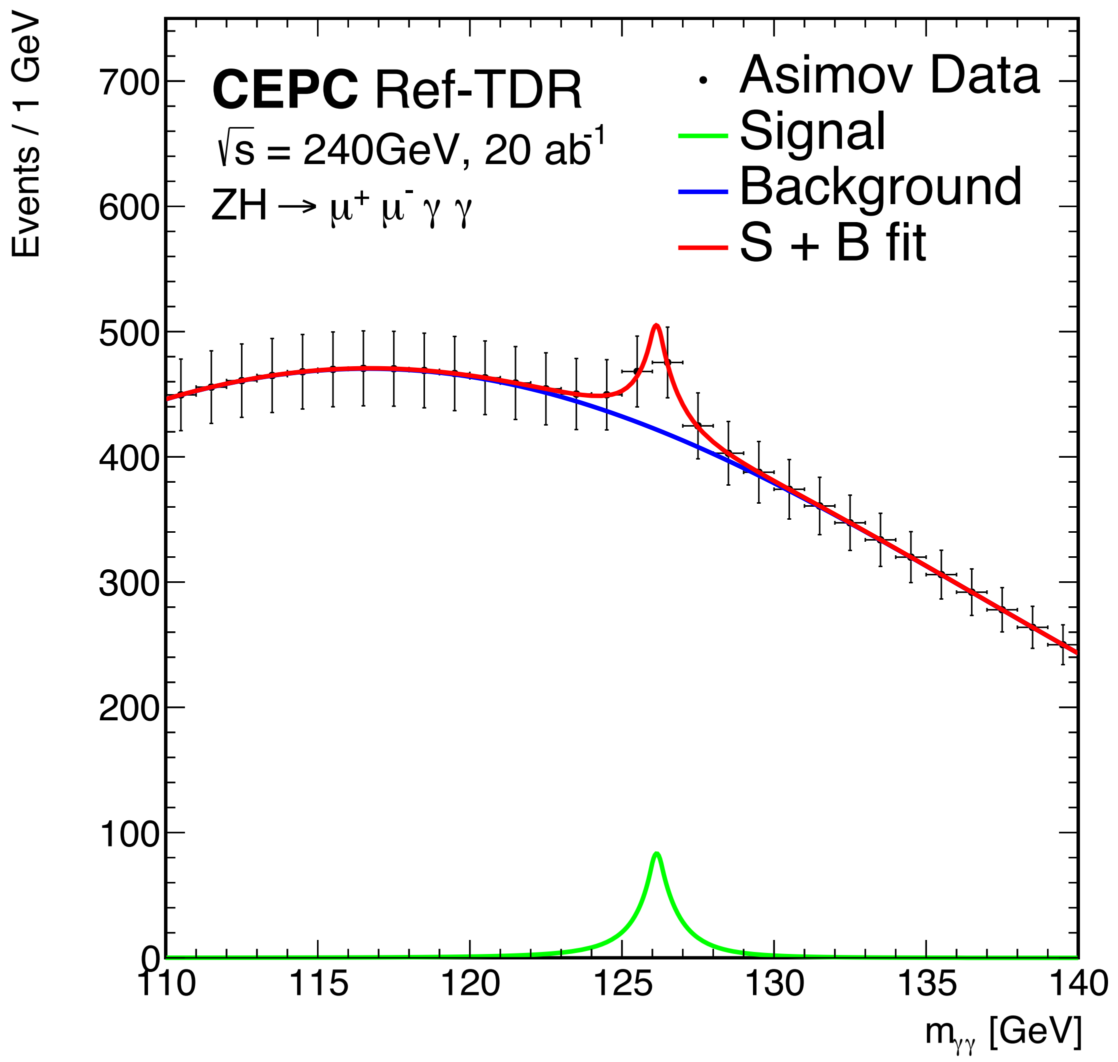
Sig	$H\to b\bar{b}$	$H\to c\bar{c}$	$H\to gg$	$H\to ZZ^*$	$H\to WW^*$	$H\to s\bar{s}$
Branching fraction	57.7%	2.91%	8.57%	2.64%	21.5%	4.4×10^(-4)
Rel. Stat. Un.	0.3%	2.2%	1.3%	7.8%	1.2%	98.8%
Rel. Syst. Un.	0.1%	1.9%	1.7%	1.0%	0.9%	179.0%

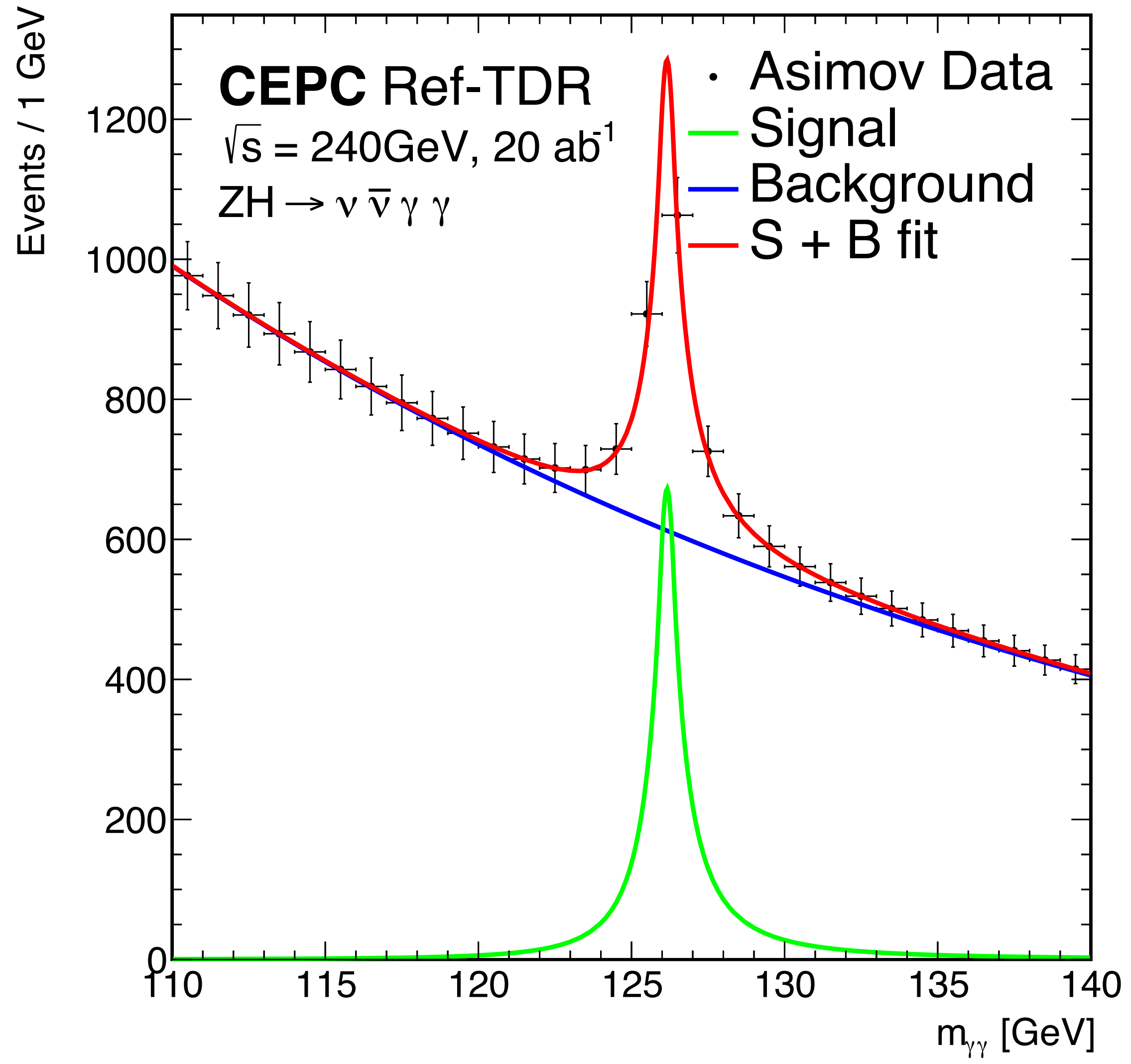
$H \to \gamma\gamma$ measurement



$Br(H \to \gamma\gamma) \sim 0.2\,\%$





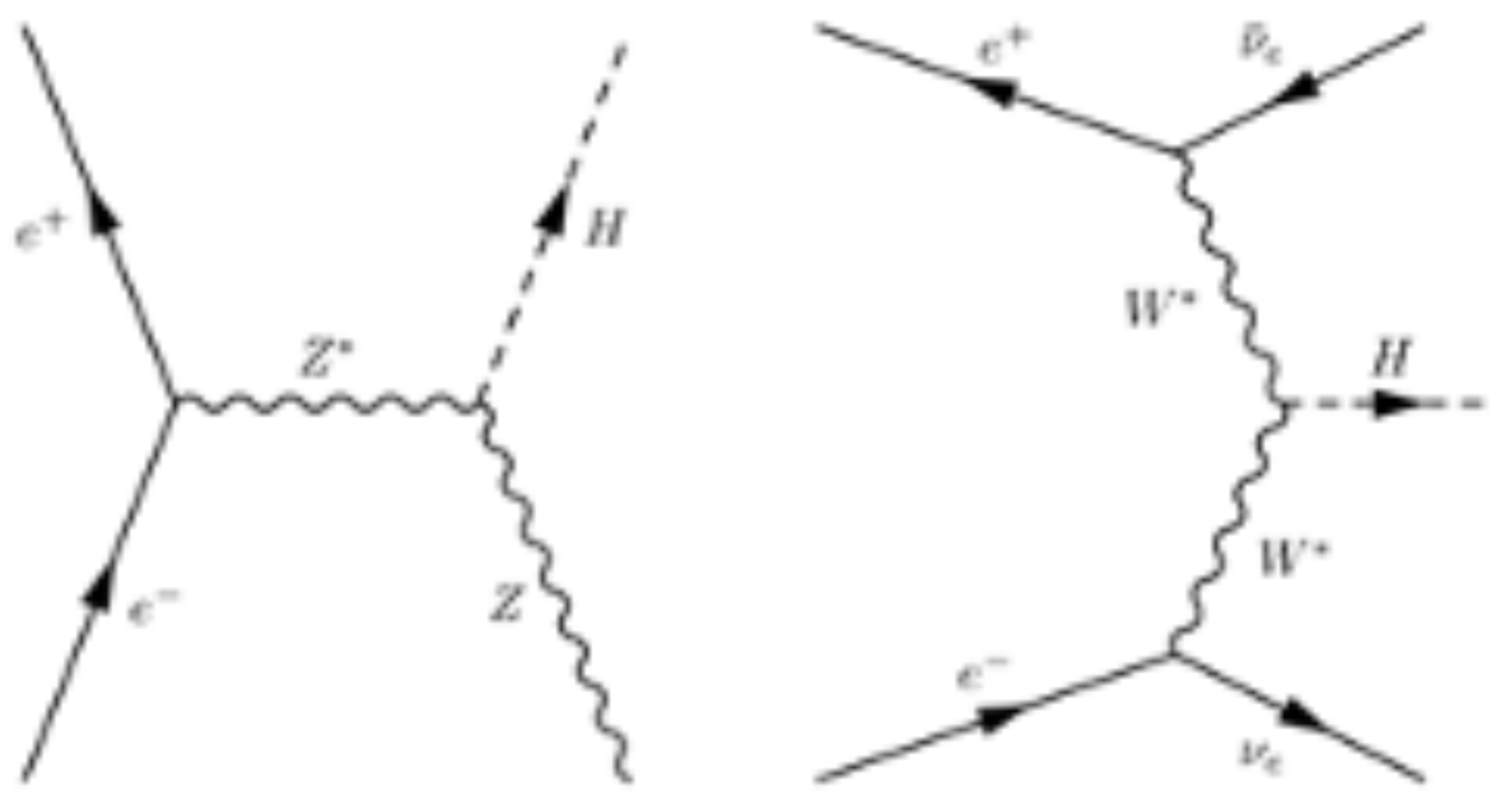


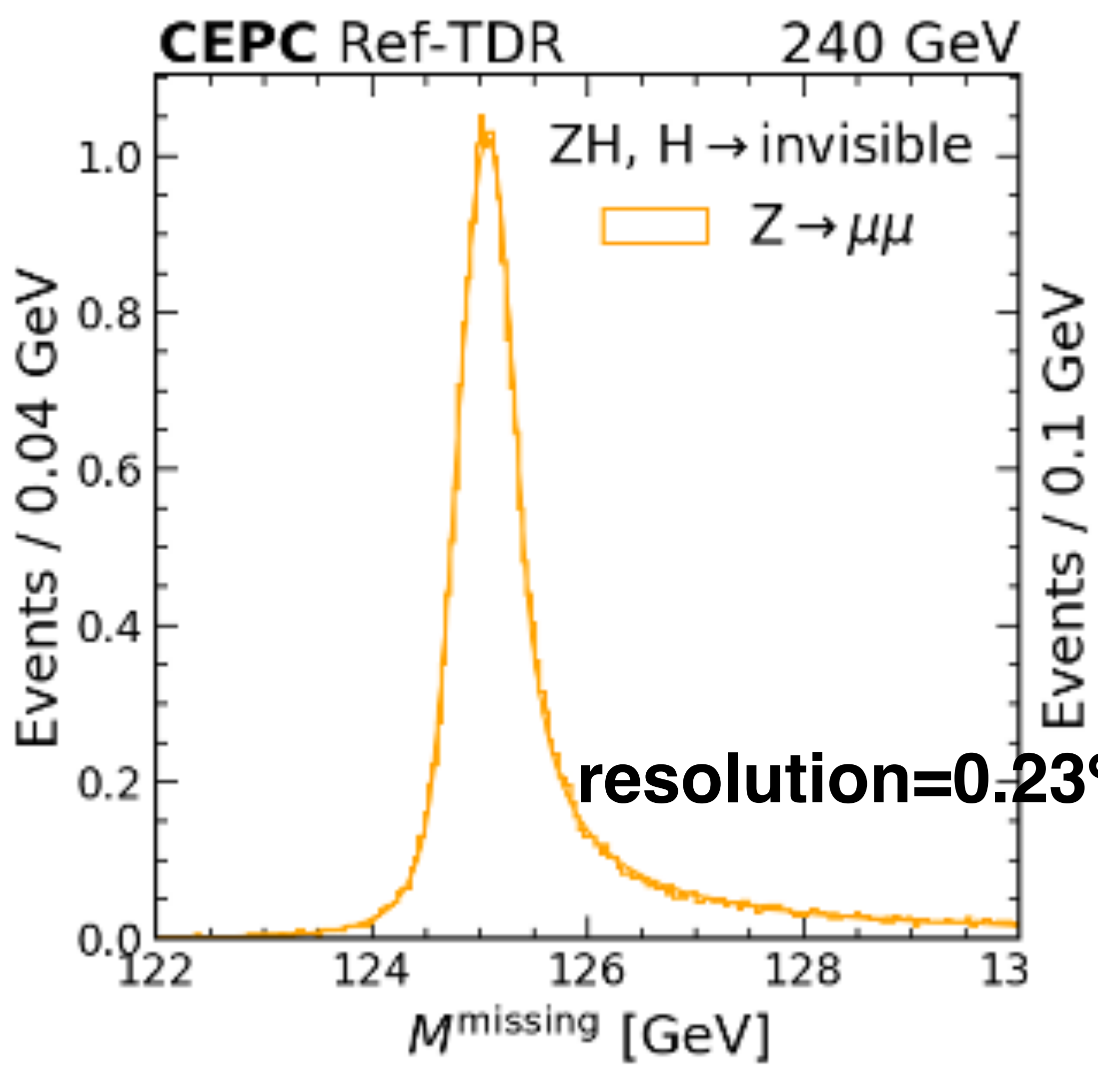
- Include ZH production mode with $Z \to q\bar{q}/\mu^+\mu^-/\nu\nu$ and $H \to \gamma\gamma$
- Sensitivity optimized with MVA in all the 3 Z-decay modes
- The combined sensitivity is ~3.2%
- Expected 15% degradation from the systematic impact

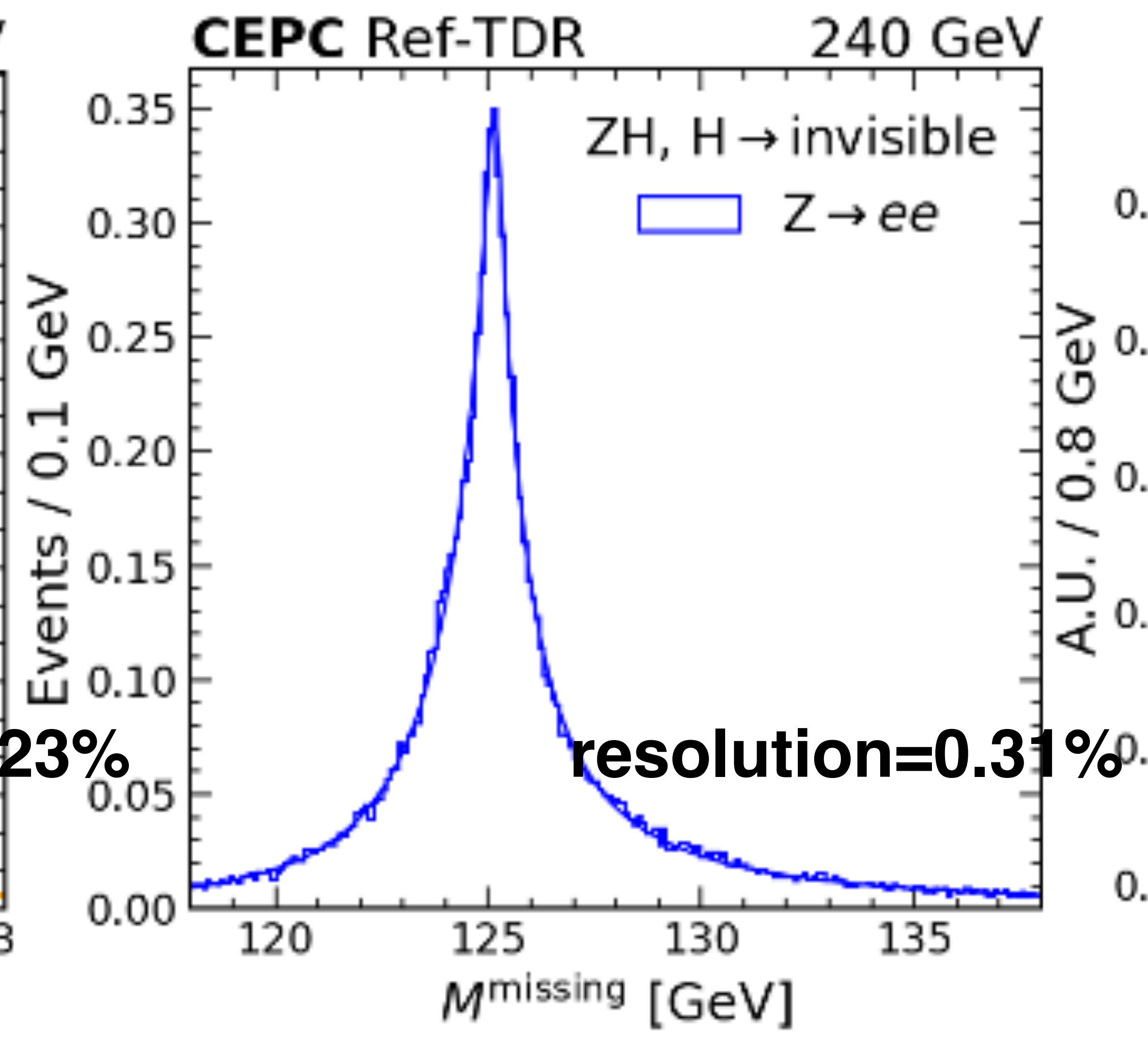
	$\Delta(\sigma \times \mathrm{Br})/(\sigma \times \mathrm{Br})_{SM}$
$q\bar{q}\gamma\gamma$	0.039
$\mu^+\mu^-\gamma\gamma$	0.160
$\nu\bar{\nu}\gamma\gamma$	0.050
Combined	0.032

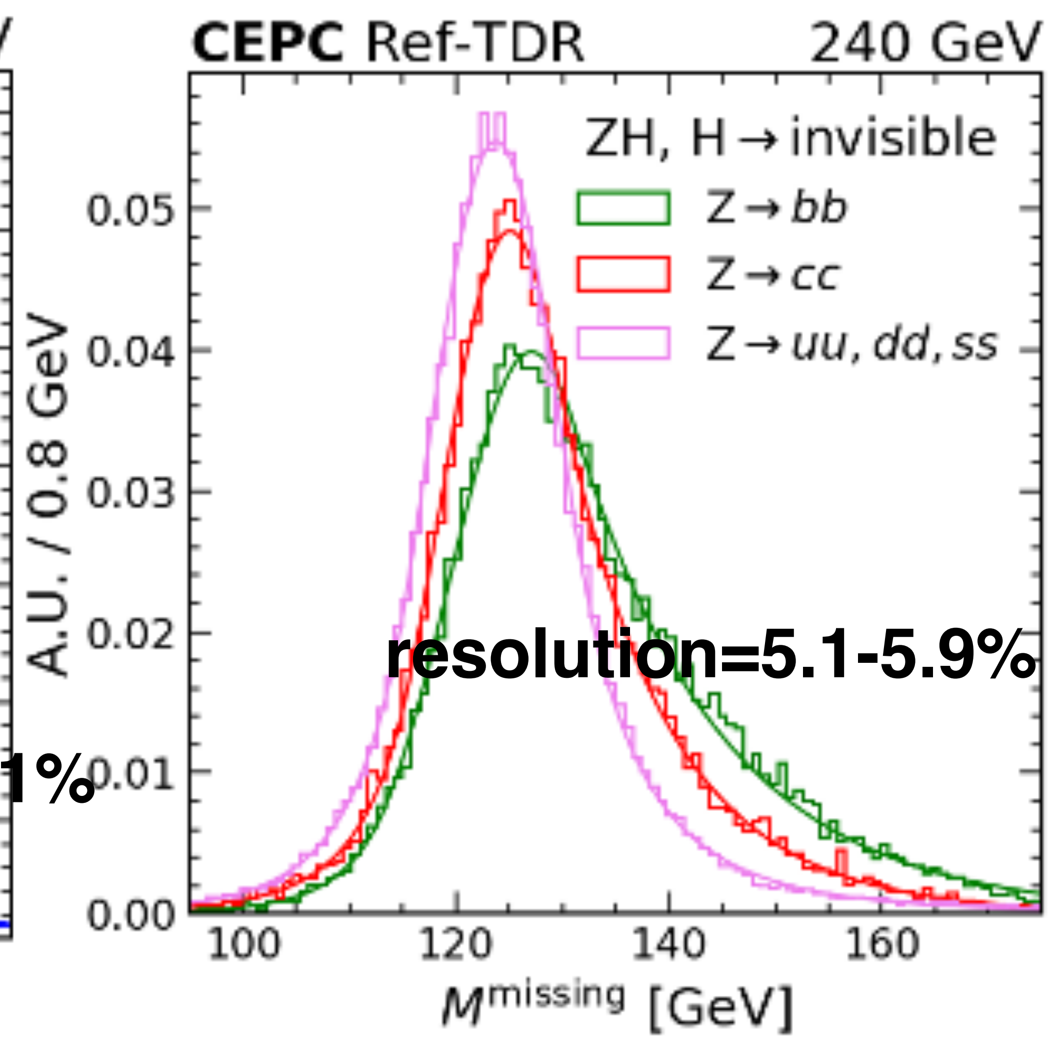
More details in Rada's talk later

$H \to$ invisible measurement





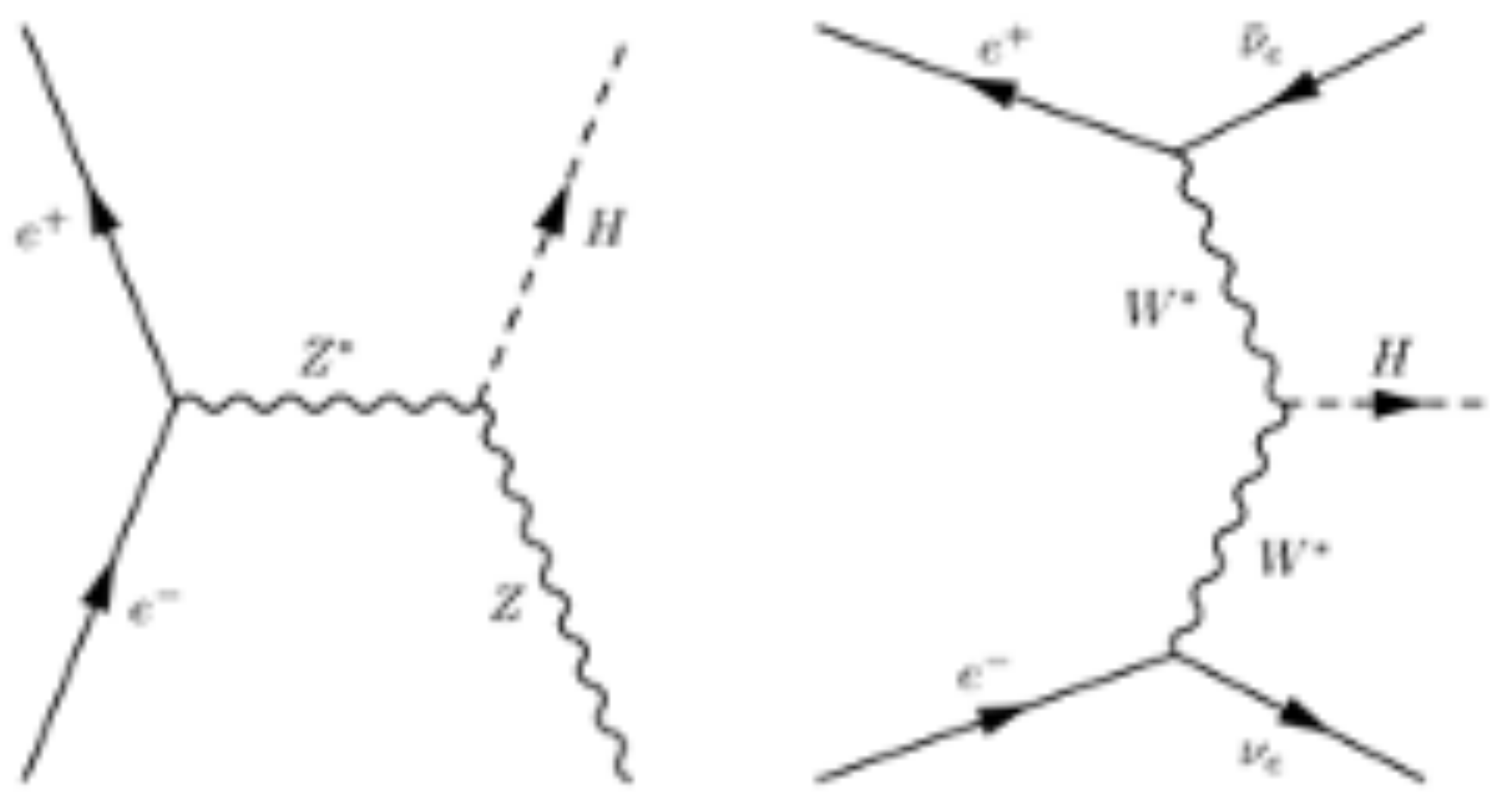


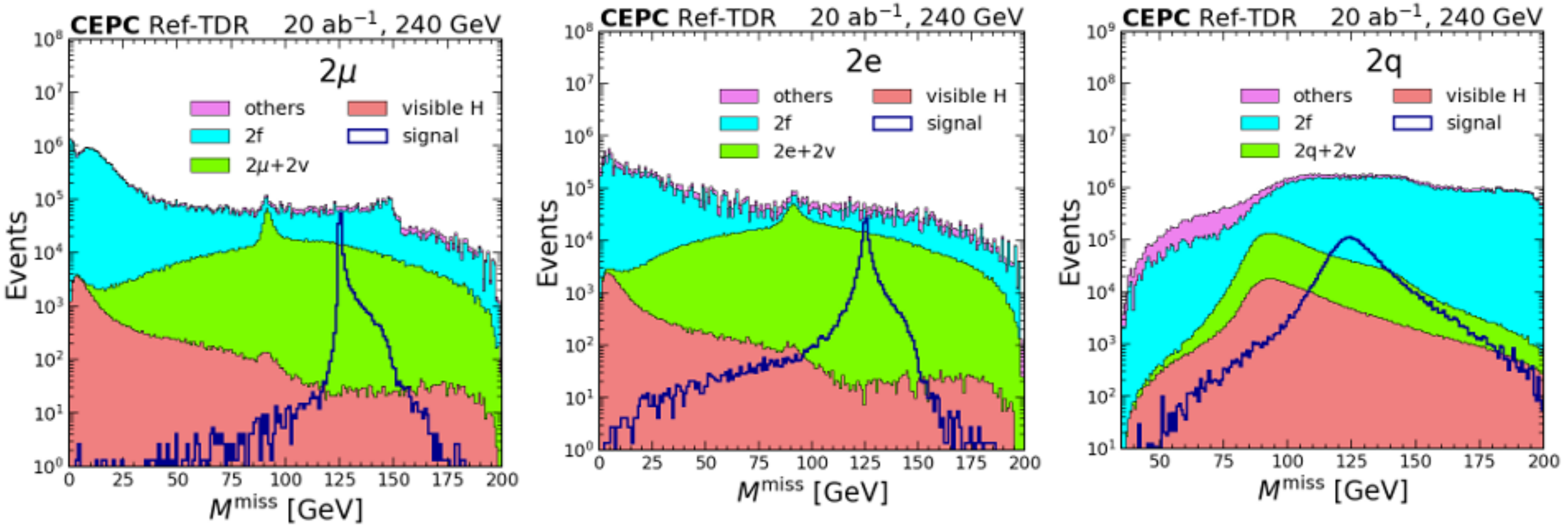


Exps	Data	UL on BR(H→inv)	Publication
ATLAS	LHC Run 2	10%	JHEP08(2022)104
CMS	LHC Run 2	10%	PRD 105 (2022) 092007
ILC	250, 350, 500 GeV; 250, 350, 500 fb-1	0.26%	arXiv:1909.07537
FCC-ee	240+365 GeV; 10.8+3 ab-1	3.9 σ on BR(ZZ→4v)	Presentation
CEPC	240 GeV, 5.6 ab-1	0.26%	Chinese Phys. C 44 123001

- In SM, $H \to$ invisible is via $H \to ZZ^* \to 4\nu$ with Br of 0.106%
- Focus on the ZH, $Z \to \mu^+\mu^-/e^+e^-/q\bar{q}$
  - Z-missing mass resolutions: 0.23%, 0.31%, 5.1-5.9%
  - Low signal/background ratio with simple selection

$H \rightarrow$ invisible measurement





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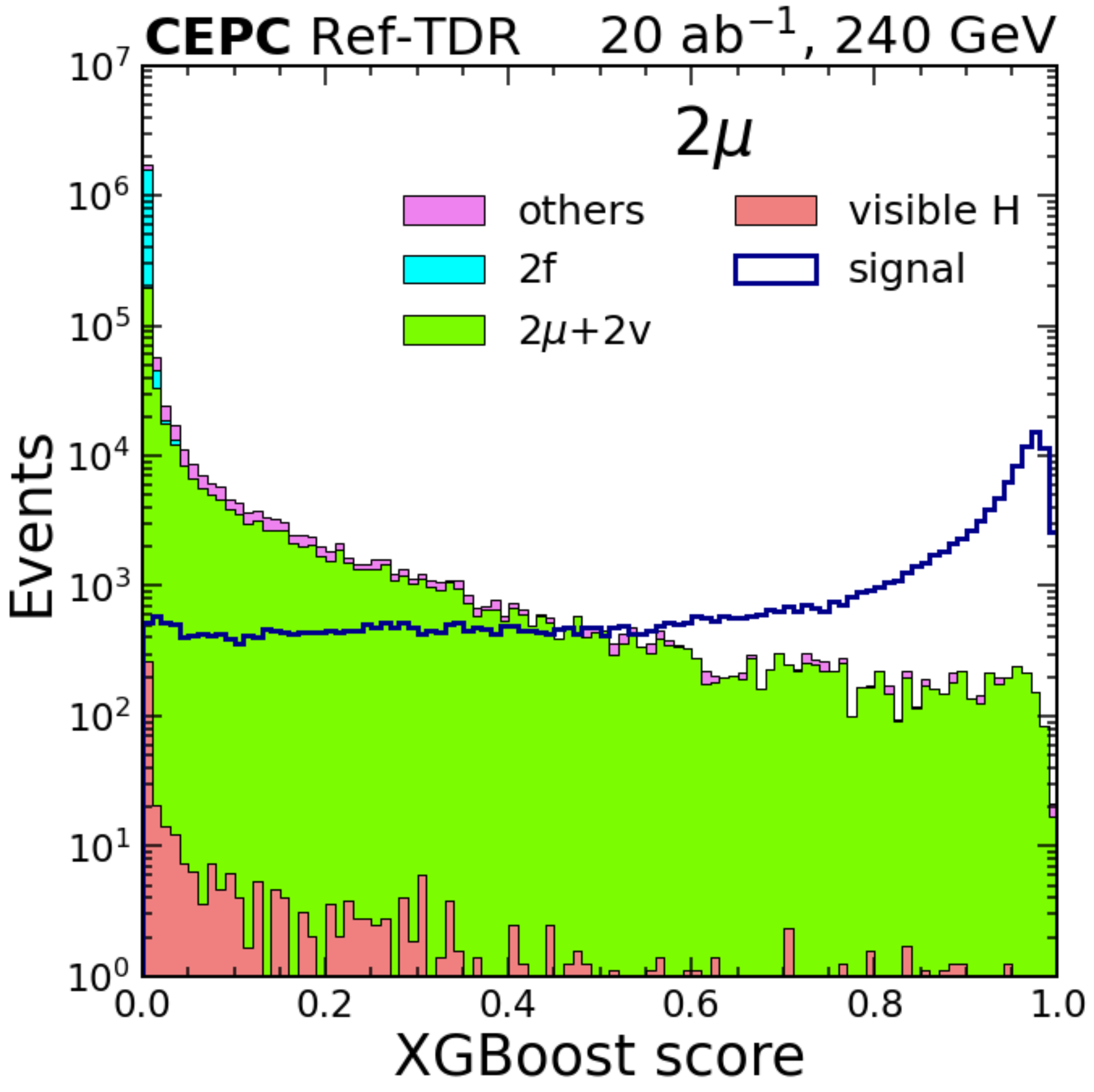
ML-based discriminant

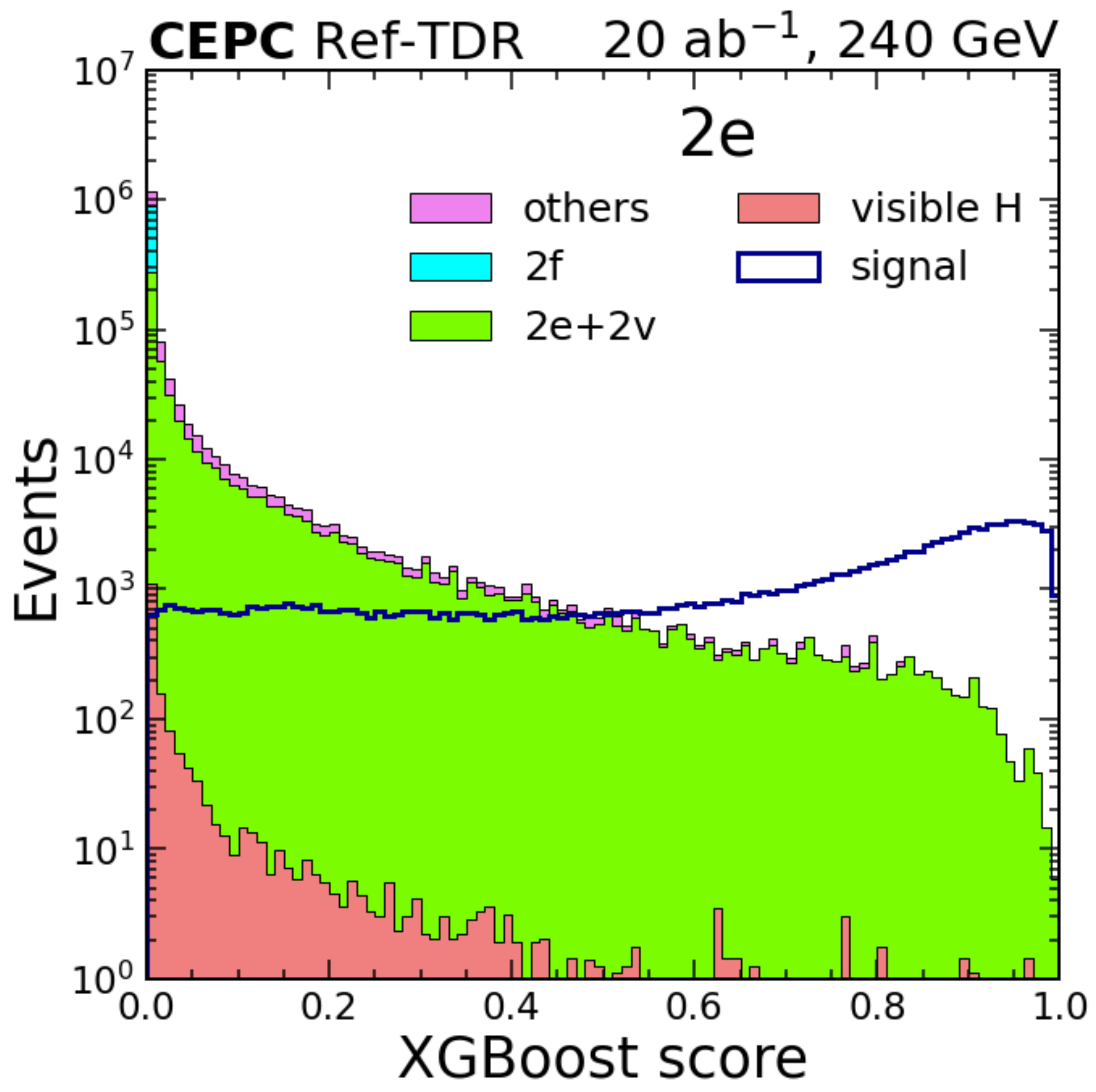
2mu channel:

- $E_{\mu\mu}, M_{\mu\mu}, P_{\mu\mu}, P^T_{\mu\mu}$
- M_{recoil}
- $E_{visible}, M_{visible}, P_{visible}, P^T_{visible}$
- $M_{missing}$
- $\Delta\phi_{\mu\mu}, \Delta R_{\mu\mu}$
- $D_0^{\mu_1}, D_0^{\mu_2}, Z_0^{\mu_1}, Z_0^{\mu_2}$
- $N_{charged}, N_{neutral}, E_{neutral}$



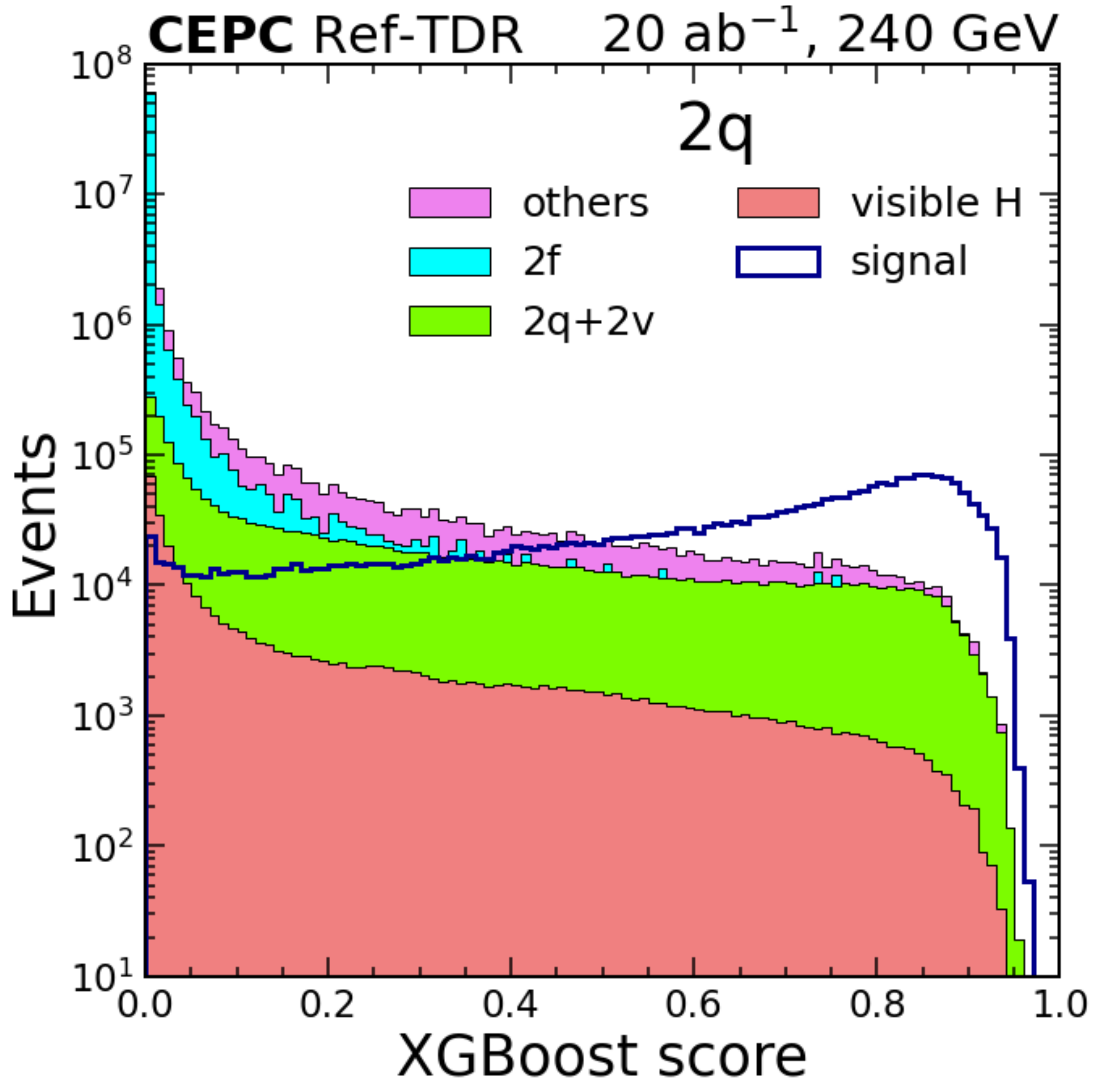
2e channel:

- Same as 2mu, except changing μ to e



2q channel:

- $E_{visible}, M_{visible}, P_{visible}, P^T_{visible}$
- $M_{missing}$
- $\Delta\phi_{jj}, \Delta R_{jj}$
- $N_{charged}, N_{neutral}$
- $N^{j_1}_{charged}, N^{j_2}_{charged}$
- $ECF_2^{j_1}, ECF_2^{j_2}$ (energy correlation function)
- $\left(\frac{\tau 3}{\tau_1}\right)^{j_1}, \left(\frac{\tau 3}{\tau_1}\right)^{j_2}$ (N-subjettiness)



$H \rightarrow$ invisible results

	5.6 ab^{-1}				20 ab^{-1}		
channel	unc	CEPC-v4	significance	UL (%)	unc	significance	UL (%)
2μ	$^{+84.3\%}_{-80.4\%}$	222%	1.25 σ	0.179%	$^{+44.1\%}_{-43.1\%}$	2.36 σ	0.093%
$2e$	$^{+124.4\%}_{-100.0\%}$	428%	0.86 σ	0.266%	$^{+64.9\%}_{-62.6\%}$	1.62 σ	0.137%
$2q$	$^{+57.8\%}_{-57.6\%}$	90%	1.74 σ	0.121%	$^{+30.6\%}_{-30.5\%}$	3.28 σ	0.064%
combine	$^{+44.3\%}_{-43.7\%}$	82%	2.31 σ	0.092%	$^{+23.4\%}_{-23.2\%}$	4.36 σ	0.049%

- Two scenarios:
  - SM $H \rightarrow$ invisible as a signal: expected uncertainty and statistical significance
  - BSM $H \rightarrow$ invisible as a signal, while the SM one as a background: expected upper limits
- With 20ab-1, it reaches 4.36σ, close to discovery level

Conclusion

- Based on TDR-Ref, some physics benchmarks are achieved:
  - Higgs mass measurement with the precision of 4.8MeV
  - Simultaneous measurement on Higgs decays to hadronic final state with the precision of ~0.4% for $H \to b\bar{b}$
  - $H \to \gamma\gamma$ branch ratio measurement with sensitivity of ~3.2%
  - With 20ab-1, Higgs to invisible decay reaches 4.36σ, close to discovery level
- More promising and comprehensive results are expected with advanced technics and detail consideration